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Transmission Stability Enhancement using Wide Area Measurement Systems (WAMS) and Critical Clusters

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Abstract

Due to the on-going worldwide trend towards investment in de-regulated electricity markets driven by political, economic and environmental issues, increasing interconnection between modern power systems has made power system dynamic studies much more complex. The continuous load growth without a corresponding increase in transmission network capacities has stressed power systems further and forced them to operate closer to their stability limits. Large power transfers between utilities across the interconnections stress these interconnections. As a result, stability of such power systems becomes a serious issue as operational security and reliability standards can be violated. On the other hand, the evolving technology of Wide-Area Measurement Systems (WAMS) has led to advanced applications in Wide-Area Monitoring, Protection and Control (WAMPAC) systems [1], which offer a cost-effective solutions to tackle these challenging issues.

The main focus of this research project was to develop a wide-area based stability enhancement control scheme for large interconnected power systems. A new method to identify coherent clusters of synchronous generators involved in wide area system oscillations was the initial part of the work. The coherent clusters identification method was developed to utilise measurements of generators speed deviation signals combined with measurements of generators active power outputs to extract coherency property between system's generators. The obtained coherency property was then used by an agglomerative clustering algorithm to group system's generators into coherent clusters. The identification of coherent clusters was then taken as a base to propose a new structure of a WAMS based stability control scheme. The concept of WAMS and a nonlinear control design approach (fuzzy logic theory) was used to provide a comprehensive new control algorithm. The objectives of the developed control scheme were to enhance and improve the control performance of modern power systems. Thus, allowing improved dynamic performance under severe operation conditions. These objectives were achieved by means of enhanced damping of power system oscillations, enhanced system stability and improved transfer capabilities of the power system allowing the stability limit to be approached without threatening the system security and reliability.

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Contents

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
AFPSS	Adaptive Fuzzy Logic Power System Stabiliser
AGC	Automatic Generation Control
AVR	Automatic Voltage Regulator
CC	Coherent Cluster
COI	Centre of Inertia
CPSS	Conventional Power System Stabiliser
DC	Direct Current
DFIG	Doubly Fed Induction Generator
DFT	Discrete Fourier Transform
DIgSILENT	Digital Simulator of Electric Networks
EEAC	Extended Equal Area Criterion
EMF	Electromotive Force
EMS	Energy Management System
FACTS	Flexible AC Transmission Systems
FLC	Fuzzy Logic Control
FLPSS	Fuzzy Logic Power System Stabiliser
FLS	Fuzzy Logic system
FPSS	Fuzzy Logic Power System Stabiliser
GA	Genetic Algorithms
GFPSS	Global Fuzzy Logic Power System Stabiliser
GPS	Global Positioning System
IDVSFPSS	Indirect Variable Structure Adaptive Fuzzy Logic Power system Stabiliser
LMI	Linea Matrix Inequalities
LFPSS	Local Fuzzy Logic Power System stabiliser
LPSS	Local Power System Stabiliser
MF	Membership Function
MISO	Multiple-input Single-output
NSSD	Normalised sun-squared deviation index

PDPSS	Proportional Derivative type Power System Stabiliser
PMU	Phasor Measurement Units
PSS	Power System Stabiliser
RFPSS	Robust adaptive Fuzzy Logic Power system stabiliser
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SFLC	Simplified Fuzzy Logic Controller
SFLPSS	Simplified Fuzzy Logic Power System Stabiliser
STFLPSS	Self-tuned Fuzzy Logic Power System stabiliser
SPSS	Supervisory level Power System Stabiliser
SVC	Static VAR Compensator
TCSC	Thyrisior Controlled Series Capacitor
WAMS	Wide-Area Measurement System
WAMPAC	Wide-Area Monitoring, Protection and Control
WSSE	Weighted Sum Squared Error

List of Symbols

ω	Generator rotor speed (rad/sec)
Δω	Generator rotor speed deviations (p.u)
$\Delta\acute{\omega}$	Derivative of rotor speed deviations (p.u)
$\overline{\Delta\omega}$	Weighted average speed deviation of an area within a power system (p.u)
A_i & A_j	Areas *i* and *j* within a power system
T	Simulation time period (seconds)
t	Simulation time sample instant (seconds)
d_{ij}	Dissimilarity coefficient between generator *i* and *j*
d_{rs}	Dissimilarity coefficient between cluster *r* and *s*
N_r	Number of generators in cluster *r*
N_s	Number of generators in cluster *s*
N_g	Number of generators in the system
P_e	Active power (Watts)
ΔP_e	Active power deviations (p.u)
Q	Reactive Power (Var)
δ_{COI}	Centre of Inertia of the system (degrees)
δ	Generator rotor angle (degrees)
V	Voltage (Volts)
I	Current (Amps)
f	Frequency (Herts)
V_{ref}	Voltage reference (p.u)
P_{ref}	Power reference (p.u)
ω_f	Speed set point (p.u)
E_f	Excitation voltage (Volts)
I_f	Field current (Amps)
P_{tie}	Active power transfer across a tie-line (Watts)
ΔP_{tie}	Derivative of active power transfer across a tie-line (p.u)
S	Generator nominal power (VA)
e	Output error

$\dot{e}$	Derivative of output error
u_{pss}	Controller output
K	Input/output scaling factor or controller gains (p.u)
$F(x)$	Membership function
μ	Degree of membership function
σ	Constant to identify the spread of a membership function
X	Control variable
X_{range}	Range of a control variable X
X_{max}	Maximum value of the control variable X
X_{min}	Minimum value of the control variable X

Chapter 1: Introduction

1.1. Today's Challenges for Power Systems Operation and Control

The complexity of operating and controlling large interconnected power systems is increasing as power systems expand in size and experience significant changes in their operational criteria. Besides the increase in size, these changes are also due to the introduction of new generation technologies in the form of distributed generators and renewable energy resources. Transmission networks in many countries around the globe are being squeezed between two conflicts. On the one hand, the continuous increase on the demand for electricity, the privatization and the deregulation of the electricity markets and the economic pressures are pushing transmission and grid operators to maximize the use of transmission assets. On the other hand, rising concerns about the reliability of supply, especially following the 2003 major grid blackouts in North America and Europe [2], are forcing the same players to be more careful about how far they can push the grids' infrastructure without risking the systems' security. Clearly, the aforementioned conflicts can be faced, at the most basic level, by responses in two forms; which are:

- Strengthening the networks by building more transmission lines and expansion of the infrastructure, or
- Maximizing the use of the existing networks by improving the level of controllability over these networks and making sure that they are operated in an efficient way; hence enhanced utilisation of these assets.

However, taking into account the cost, time, and environmental related issues, it seems that the first course of action, which is enforcement of transmission networks by adding new transmission lines and infrastructure enforcement, is not the favourite solution to these challenges. In contrast, utilities nowadays are focusing more than ever on utilizing their existing systems to their maximum capacities, keeping in mind the importance and essential aspects of maintaining high standards of reliability, security and quality of supply. With limited capability to strengthen generation and transmission networks due to environmental and cost constraints, utilities are faced with the need to relay on active control so as to improve the systems' performance under stressed operation conditions.

Better visualization and assistance tools for operators in regional control centres are required to be developed so as to allow for better management of the power grids. Closed-loop control actions for events beyond response time for manual control are needed to be designed so as to enable fast corrective measures that reconfigure the system to arrest system collapse and prevent supply interruptions.

In conclusion, the complexity as well as the volatility of the operational tasks of power systems is increasing. This requires essential and necessary further development of tools to operate and control these systems in a reliable manner by making use of recent developed technologies in many other fields of engineering, such as communication technology and IT development.

1.2. Responses to the Challenges

As mentioned above, modern power systems in many countries are experiencing significant changes in their operational criteria and are, consequently, facing a number of challenges. The outcome of most of these challenges is that pressure has been put on these systems and on grid operators to maximize the utilization of high voltage equipment which, in turn, has led to the operation of this equipment closer than ever to its stability limit. The approach of maximum utilizations of existing assets is possible providing that these systems are equipped with well-designed and well-coordinated protection and control schemes that ensure safe and stable operation of these systems. Design of such schemes can be possible by introducing new technologies and utilizing these technologies in the area of power systems operation and control.

Recent developments in measurement, communications, and analytical technologies have introduced a range of new options. In particular, the evolving technology of Wide-Area Measurement Systems (WAMS) and the use of Phasor Measurement Units (PMUs) have made the monitoring of the dynamics of power systems in real-time a promising aspect to enhance and maintain systems stability under stressed operation conditions. The development of the synchronised Phasor Measurement Units (PMUs), which use advances in communications, computation capabilities and Global Positioning System (GPS) technologies, provides the bases of Wide-Area Measurement

Systems (WAMS), which are needed for monitoring and managing stressed power systems. The interest in phasor measurement technology has received a great deal of attention in recent years as the need for the best estimate of the power system's state is recognised to be crucial element in enhancing its performance and its resilience to catastrophic failures. The information captured by these types of measurement systems not only allows for better monitoring of the power system, but also provides the required tools to design proper control and protection schemes based on wide-area dynamic systems information. Such schemes will enable enhancement of power systems performance and, as a result, will help to ensure that the challenges are met effectively. Wide-Area Measurement Systems (WAMS) open a new path to power system stability analysis and control. These systems are capable of providing dynamic snapshot of the systems states in real-time and update it every 20 ms [3]. Having such a precise understanding of the operation conditions contributes significantly to achieving much improved performance levels of power systems. The effectiveness of the design of control schemes based on wide-area information can also contribute to better systems utilization. The enhancement of the system performance based on WAMS technologies includes [4]:

- Avoiding large area disturbances.
- Improving exploitation of existing assets.
- Increasing power transmission capability with no reduction of system security.
- Better access to low-cost generation.
- Better visualization and assistance tools for operators to manage the system.
- Assuring power system integrity.

Installing the phasor measurement units (PMUs) and acquiring the important information about the PMU/WAM system through continuous observations of system events have been the first step followed in most countries that are starting to implement these technologies [5]. Most installations are aiming for a wide-area measurement system (WAMS) in which measurements obtained from various locations on the system can be collected at central locations. From those central locations wide range of monitoring, protection and control applications can be deployed.

1.3. Thesis Overview

The challenges facing today's highly complex interconnected power systems vary as mentioned above. Some of these challenging issues are due to increase in demand and difficulties in simple expansion and enforcement of the network. Others are due to the introduction of new generation technologies and the need to integrate these technologies with the existing infrastructure in a flexible way. It is a challenging task to try to define all the problems and find solutions to all of them. Nonetheless, the way to go about these issues is to break them into smaller tasks and address each individually.

One of the rising concerns, believed to cause limitation in the amount of power transfer across transmission networks, is power system oscillations and their impact on the stable operation of power systems. Power system oscillations at low frequencies are some of the earliest power system stability problems. They are related to the small signal stability of power systems and are detrimental to the goal of maximum power transfer and power system security [6]. Early attempts to control these oscillations include using damper windings on the generator rotors and turbines, which found to be satisfactory at the time. However, as power systems began to operate closer to their stability limits, the weakness of a synchronising torque among the generators was recognised as a major cause of system instability to which the introduction of Automatic Voltage Regulators (AVRs) helped to tackle the issue and improve the steady state stability of the power system. The issue of transferring large amounts of power across long transmission lines arise with the creation of large interconnected power systems. The addition of supplementary controllers into the control loop, such as the introduction of Conventional Power System Stabilisers (CPSSs) to the AVRs control loop on the generators, provides the means to reduce the inhibiting effects of low frequency oscillations which limit the amount of power transfer. The conventional power system stabilisers work well at the particular network configuration and steady state conditions for which they were designed. Once conditions change their performance deteriorate.

As power systems are becoming more complex, the need for maximum utilisation is becoming a necessity. Hence the need for new control schemes to improve system stability and allow for such maximum utilisation to be visible without compromising system security and reliability is becoming the focus of system operators and research development. The development of such schemes requires essential and necessary further development of tools to operate and control these systems in a reliable manner by making use of recent developed technologies in many other fields of engineering, such as communication technology and IT development.

The issue of dealing with power system oscillations and enhancement of transmission stability is the overall aim of this research. The aim is to focus on implementing the aforementioned WAM based systems to address and tackle the problem of power system oscillations in power systems. As power systems tend to form Coherent Clusters (CC) or areas when they oscillate, then this concept is taken as bases to develop an algorithm that identifies these coherent clusters (CC) of synchronous machines. The identification algorithm uses wide-area signal measurements to determine clusters of coherent generators involved in system oscillations. The identified clusters are then taken as a base to develop a wide-area based control scheme in the form of wide-area based power system stabiliser. The developed control scheme provides a comprehensive control technique that cooperates with existing controllers to ensure that the overall system stability control performance is enhanced. The aim of the proposed controller is to overcome the drawbacks of conventional power system stabilisers by providing enhanced control signals based on wide-area information. The developed wide-area based stabiliser is designed using fuzzy logic control design approach and referred to as **G**lobal **F**uzzy **P**ower **S**ystem **S**tabiliser (GFPSS). The performance of the proposed fuzzy logic stabiliser is validated and compared with conventional power system stabilisers using standard test systems of different topologies and configurations. The research objectives are set in the following section.

1.4. Research Objectives

In this research, the following objectives are set:

- Development of a new technique that is suitable for implementation in WAMS to identify coherent cluster and, therefore, critical areas for potential control in large interconnected power systems.

- To combine the identification of coherent clusters technique with a mechanism to determine which cluster is more critical for the system stability. This is important, from control and operation points of view, for the design of stability control schemes to arrest system instabilities. Identification of critical areas makes the determination of critical tie-lines (those lines that connect the clusters to each other) possible by visual inspection to the network topology. Such critical lines, where system oscillations are highly observable, can be an important source of providing wide-area based information.

- Development of new wide-area based stability controller that form a second level of control measure complementary to conventional control schemes. The developed controller is a power system stabiliser designed using non-linear control design approach and utilises wide-area information extracted from coherent areas as remote control signals. The global fuzzy power system stabiliser (GFPSS) acts between the coherent areas to provide additional stabilising signals based on wide view of the system. The additional stabilising signals are added to the local control signals provided by local power system stabilisers to allow for enhanced cooperation between local controllers. The GFPSS is designed to cooperate with conventional controllers (Conventional Power System Stabilisers CPSS) to rapidly reconfigure the system to arrest system collapse when lower levels of control run out of resources.

- To demonstrate that the new control scheme will enhance the level of controllability over existing power systems allowing for better transmission capabilities and hence better utilisation of these systems.

1.5. Thesis Structure and Content

Chapter 1:

This chapter presents an introduction to the challenges faced by power systems in recent times. It briefly describes the reasons that are causing problems to have an impact on the secure and reliable operations for modern power systems. It also introduces the available actions and methodologies to deal with these challenges and provide alternative solutions. The chapter also describes the thesis overall view and sets the research objectives and contribution.

Chapter 2:

This chapter discusses the bases of wide-area measurement systems (WAMS) and their applications in power systems. The architecture of a PMU/WAMS based system is illustrated indicating their advantages over the traditional RTU/SCADA systems. Also a general view of WAMS applications in the areas of monitoring, control and protection of power systems is included.

Chapter 3:

This chapter presents the issue of power system oscillations, which is believed to cause limitation in the amount of power transfer across transmission lines in increasingly interconnected power systems. A number of recently developed wide-area based control schemes for power system oscillation damping are investigated considering different design approaches such as; decentralised control strategies, centralised control strategies and multi-agent control strategies. The concept of Coherent Clusters (CC), which is related to the oscillation of coherent groups of synchronous generators in multi-machine power systems, is explored. Literature surveys on a number of developed techniques used to identify the coherent clusters in power systems are presented.

Chapter 4:

This chapter introduces a new technique that is based on wide-area signal measurement to identify the coherent clusters in a multi-machine power system. The methodology of the proposed technique is described and tested. Also the results obtained are presented and discussed to demonstrate the robustness and the effectiveness of the algorithm in identifying the coherent clusters.

Chapter 5:

This chapter adds to chapter 4 the possibility of evaluating the identified clusters in terms of their criticality to the system stability. Having identified coherent clusters in a given power system, it becomes possible to develop techniques to identify which cluster is more critical for the system stability. It also becomes possible to identify critical tie-lines (those lines that connect the clusters to each other) by visual inspection to the network topology. Such critical lines, where system oscillations are highly observable, can be monitored and wide-area measurement devices can be located. Remote signals from these critical tie-lines and these coherent areas can be acquired using WAMS synchronised measurements and then used as wide-area remote feedback signals to wide-area based oscillation damping controllers. This approach is taken as the bases to develop a wide-area based fuzzy logic power system stabiliser, developed and tested in the following chapters (chapter 6 and 7).

Chapter 6:

This chapter presents a novel WAM based control scheme that uses global power system stabiliser as a tool for system stability enhancement. The limitation and drawbacks of existing conventional power system stabilisers CPSS are indicated. An alternative non-linear control design approach using fuzzy logic theory is explored in details. A brief description of application of fuzzy logic theory in different areas of power systems' operation, planning and control is also included. This is followed by a detailed discussion of the design procedures and the applications of fuzzy logic based power system stabilisers as stability enhancement tools. A novel design structure for a wide-area based fuzzy logic power system stabiliser is proposed. It is referred to as Global Fuzzy Power System Stabiliser (GFPSS). Initially, the structure and design of the controller is developed and presented for a two-area based power system for ease of design and simplicity of demonstration. The results obtained are analysed and discussed in details concluding the advantages of the proposed GFPSS controller. The controller structure is then generalised in the following chapter (chapter 7) for implementation in large scale power systems.

Chapter 7:

This chapter presents the general structure for the designed wide-area based damping controller which makes it visible for implementation in multi-area large power systems. The implementation strategy for the designed GFPSS is explained using a number of standard test systems as case studies. Intensive simulation scenarios are used to illustrate the impact of the proposed controller on the dynamic performance of electric power systems. The results are discussed to evaluate the performance of the proposed controller and to compare its performance with conventional stabilisers.

Chapter 8:

The final chapter presents conclusions of the thesis and explores the limitation of the work. It also provides suggestions for future work which can improve the work that has been carried out in this research.

1.6. Contribution from this Research

The overall aim of this research is the new development of an enhanced control scheme that is based on the new evolving technology of wide area measurement system to allow for better utilisation of modern power systems through the enhancement of their stability control. However, specific contributions for which this PhD thesis is claimed are:

- A structured discussion of the current challenges and difficulties faced by todays interconnected power system and the ways by which such difficulties may be dealt with in terms of utilising new technologies in the design of new control, protection and monitoring schemes.

- Discussion and examples of some of the current developed WAMS based controllers that are aimed to enhance the dynamic performance of modern power systems and allow for better system's assets utilisation.

- Detailed analysis of one of the raising concerns which puts barriers towards better utilisation of transmission networks. This is the issue of power system oscillations and its impact on the system stability and security.

- The development of a new technique to identify coherent clusters of oscillating synchronous generators based on wide-area signal measurement.

- A novel technique to identify which of the coherent clusters are more critical to the system stability, and therefore, which clusters' information can be utilised for wide-area based control enhancement scheme.

- A novel design structure of a wide-area based power system stabiliser using fuzzy logic control theory. The design is based on implementing a non-linear-fuzzy logic based power system stabiliser (Global Fuzzy Power System Stabiliser GFPSS) to act between coherent critical areas of synchronous generators. The GFPSS aim is to provide a second level of control measures complementary to conventional control schemes and, hence provide an enhanced stability control signal. The additional wide-area based signal allows for better system oscillation damping capabilities. The ability to damp power system oscillations more effectively gives system's operators the confidence to utilise the transmission network in a better way and allows for more power transfer capabilities.

Chapter 2: Wide-area Measurement Systems WAMS

2.1. Overview

The term WAMS refers to the system of wide-area measurement or wide-area data acquisition. A wide-area measurement system consists of advanced measurement technology, information tools, and operational infrastructure that facilitate the understanding and management of the increasingly complex behaviour exhibited by large interconnected power systems. Initially, WAMS were designed as a complementary system to provide power systems operators with real-time dynamic information of system conditions that is essential for safe, stable and reliable operation of the power system. However, increasing focus is being put towards incorporating these advanced technologies into the actual control system of power system networks. WAMS offer promising tools for better visualisation, better monitoring, better management, and better control of power systems.

A Wide-Area Measurement System (WAMS) is a real-time, synchronised data acquisition system used to dynamically monitor, manage, protect and control power system networks. The bases of WAMS is synchronised Phasor Measurement Units (PMUs). These are measurement units capable of providing direct measurements of the magnitudes and phasor of currents and voltages. They also have computational capabilities to extract and provide other measurements of system state variables. The merit of these measurement units relies on their capability to synchronise the measured quantities across the entire power system using timing-reference signals provided by the Global Positioning System (GPS). Hence, a dynamic snapshot of the system states can be obtained and then updated in real-time.

The GPS provides the best synchronising clock in a wide area. This is realised by the 24 modern satellites which were put in place completely in 1994. These satellites are arranged in six orbital planes around the earth. They are arranged in such a way that at least six of them are visible at most locations on earth, and often as many as 10 satellites may be available. PMUs receive a one pulse-per-second signal provided by the GPS.

This pulse as received by any receiver on earth is coincident with all other received pulses to within 1 microsecond; much better accuracies of synchronisation have been achieved (in the order of a few hundred Nano-seconds) [7]. The GPS satellites, therefore, keep accurate clocks which provide the one pulse-per-second signals that make the synchronisation of the obtained measurements by the PMUs possible. In other words, PMUs measure the real-time system state variables and then time-stamp these measurement using the GPS time reference signals. The measurements are time-stamped in time intervals down to 20 ms, which shows how accurate the dynamic snapshot of the real system is. Figure (2-1) illustrates the major elements of the modern PMU, [7].

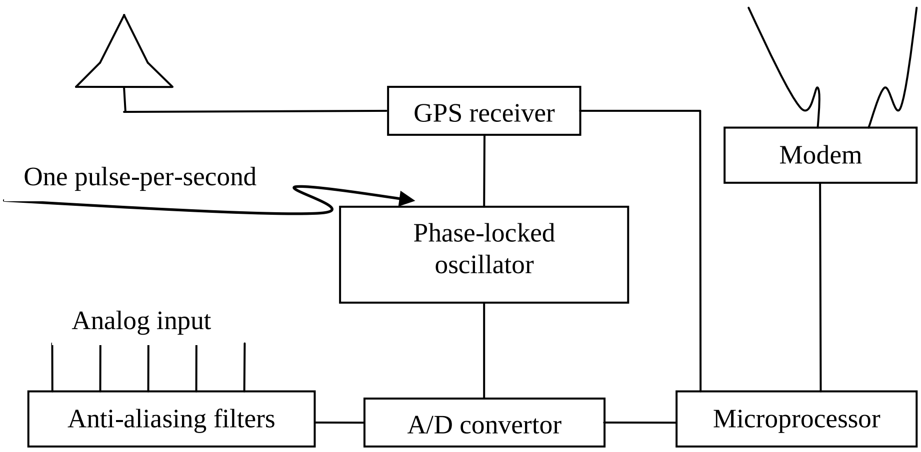

Figure 2-1: Elements of Phasor Measurement Unit PMU [7]

A Wide-Area Measurement System WAMS can be understood as an advanced Supervisory Control and Data Acquisition (SCADA) system. The main difference is that data acquired by Remote Terminal Units (RTUs) in an RTU/SCADA system is restricted to static categories and is not capable of providing dynamic view of the system. In contrast, the dynamic behaviours of power systems are presented by the synchronously collected measurement obtained by PMUs in a PMU/WAM system whose data acquisition is synchronised by the GPS time reference signals. The availability of highly accurate synchronised measurements enables new advanced levels of monitoring, protection, and control capabilities to be achieved. Hence a significant improvement can be made to utilise power systems' equipment more effectively in a reliable way. Figure (2-2) shows a simplified illustration of a Wide-Area Measurement System and its main requirements [8]. PMUs collect data from different locations of the power system network (Data Acquisition). The acquired data is synchronised using accurate synchronising signals provided by the GPS satellites (Data Synchronisation). The synchronised data is then transmitted to control centres (Data Transmission) where decisions regarding the operation and control of the power system are been made (Control Actions Deployment).

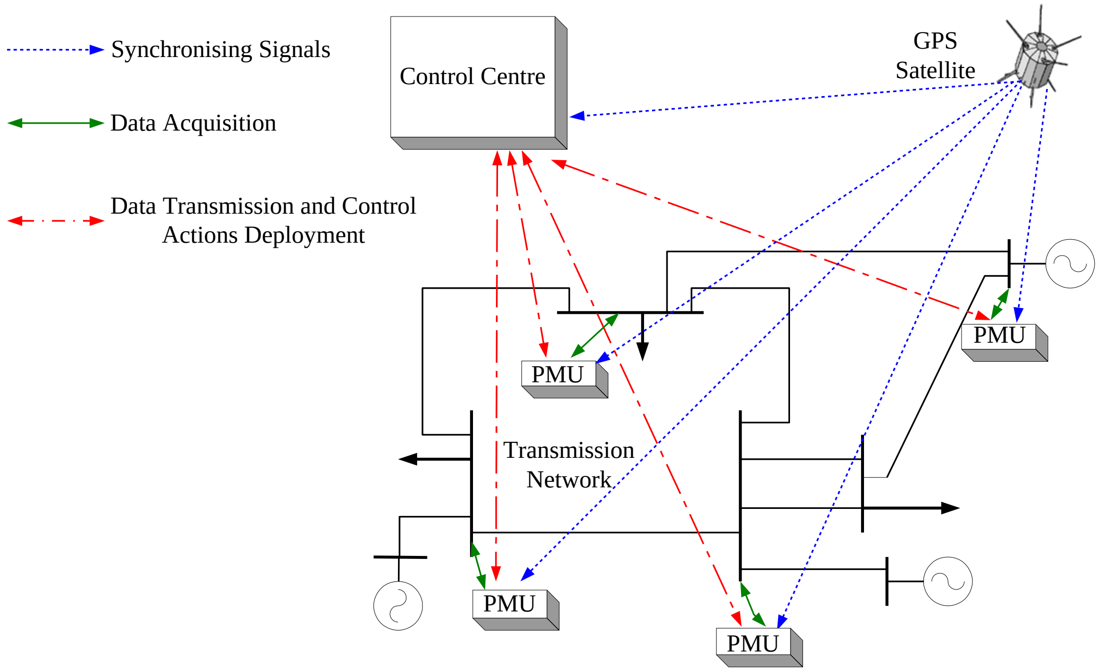

Figure 2-2: A simplified WAMS architecture [8]

The advantages of PMU/WAM based systems over the RTU/SCADA systems include the following [9, 10]:

- High-speed data acquisition with a unified time-stamp and high-speed data transfer capabilities.
- Availability of direct measurements which are time-stamped in time intervals of 10-20ms [11].
- Availability of wide area dynamic system view.
- Availability of dynamic measurements and representation of events encountered by power systems.

As a result of the availability of an accurate wide-area representation of power system networks, coordinated and optimised control schemes as well as adaptive relaying in coordination with local protective devices, which all are aimed for stable, reliable and secure operation of power system networks, become viable and possible to be developed.

2.2. WAMS Applications in Power Systems

Traditional power systems’ control and protection schemes are, in general, based on local system information. The main drawbacks of such systems are the inappropriate system dynamic view and the absence of coordination between local controllers and decentralised control and protection devices [12]. However, phenomena that threaten the stable and secure operation of power systems are of a widespread nature (i.e. the effect of an event disturbance that may cause unstable operation behaviour in one part of the network can propagate and affect other parts of the network far away from the origin of the event). This implies that it is difficult to maintain the system stability and security on the whole if only local measurements are employed in the designing of the control and protection schemes [13]. With the rising complexity in today’s power systems, a promising way of enhancing and utilising the operation, control and protection tasks is to provide a system-wide control and protection schemes, complementary to the conventional local control and protection strategies. It is understood that predicting or preventing all events that may cause deterioration of stable operation conditions of power systems, or may even lead to power system collapse, is not possible. Nonetheless, a wide-area monitoring and control system that provides reliable and optimised coordinated control actions is able to mitigate or prevent large area disturbances. The main advantages which can be accomplished through incorporating wide-area based monitoring and control systems, using WAMS applications in the area of power systems operation and control, include:

- Enhanced utilisation of power systems through well-designed and well-coordinated control actions.
- Operation closer to the limit through flexible relaying schemes.
- Early recognition as well as proper corrective measures of large and small instabilities phenomena that may be encountered by power systems.
- Fewer load interruption events, thus improvement of supply security and system reliability.

To be able to design effective control and protection schemes that ensure stable operation of power systems, it is important to understand the type, size and nature of phenomena that may be encountered by these systems, and therefore, need to be counteracted. In many cases, problems faced by power systems are formulated in general terms such as “protection against major contingencies” or “counteracting cascaded outages”. In order to address these problems, there is a need to classify them and break them down into physical phenomena that can be mitigated by designed control and protection schemes. Generally, those physical phenomena include control of and protection against [8, 14]:

- Transient angle instability
- Small signal angle stability
- Frequency stability
- Short-term voltage stability
- Long-term voltage stability
- Cascading outages

For stable, secure and reliable operation of modern power systems, well-designed robust systems have to be designed so as to arrest the impact of each of the aforementioned phenomena on power system networks. PMU/WAMS systems can be utilised in many aspects of monitoring, control and protection against such phenomena. Control and protective algorithms can be designed based on WAMS applications to provide proper measures that ensure systems stability.

WAMS applications to power systems can be recognised in three main areas: Protection, Control, and Monitoring [1]. A number of these applications are starting to evolve in many power systems around the globe. A good example are those being deployed in China [15].

2.2.1. Protection

One of the promising applications of WAMS in the area of power system protection is the possibility of developing adaptive protection schemes. Adaptive protection is a protection philosophy which permits and seeks to make automatic adjustments in various protection functions so as to allow better performance of the protection scheme. In contrast, conventional relaying is realised by compromised settings of protection relays, which are reasonable for many alternative conditions that may exist in a power system. This, however, implies that these settings may not be the best for any one specific condition. Therefore, a protection system that is capable of online setting reconfiguration based on a dynamic view of system operating conditions will significantly improve the performance of the protection function. An adaptive protection scheme may include various protection functions, such as:

- Identification of fault location based on WAMS
- Adaptive online adjustment of relay settings based on wide-area information
- Adaptive back-up protection based on WAMS

With a global view of system conditions, wide-area based protection schemes can be implemented to enhance power systems' response to disturbances by assuring that protective actions and faulty equipment/circuit disconnections are formulated precisely in an optimized way. Wide-area based protection; however, is beyond the scope of this research.

2.2.2. Control

As for protection schemes, wide-area synchronised measurement technology offers a unique opportunity to utilise wide-area system information in the design of control schemes that are aimed to enhance system performance and guarantee system stability. Generally speaking, oscillatory stability, often referred to as the issue of power system oscillations, is causing a rising concerns for system operators. This is due to increasing interconnections between utilities and increase in the amount of power transfer across these interconnections [16]. This phenomenon is classified, according to the IEEE/CEGRE Joint Task Force on Stability Terms and Definitions [6], as small signal rotor angle stability[1]. The impact of this phenomenon on the whole system can be significant as it may lead to limit the amount of power transfer between regions and, if not damped properly, can cause the collapse of the entire system. Hence, damping of

[1] This will be discussed further in chapter 3

power system oscillations between interconnected areas is an important controlling task for secure and stable operation of power systems.

Power system oscillations are of two modes [6]. Local modes, which is the notion of the oscillation of one generator or one plant in an area against the rest of the system, and inter-area modes, which are associated with the oscillations of groups of generators or plants in different areas against each other. Local modes of oscillation are largely determined and influenced by local area states and, in most cases, control measures in the form of local conventional power system stabilisers PSS [17] can be sufficient enough to deal with them and provide the required damping for the oscillations. However, oscillations in the form of inter-area modes are not as highly observable and controllable using local system observations as local modes. As a result, control measures for inter-area modes of oscillations are rather complicated and, therefore, concerns arise in this area giving the rising complexity of power systems. In addition, local conventional controllers, such as PSSs, have fixed parameters that, in most practical cases, are determined based on linearized system models and are tuned in non-optimum ways to deal with both modes of oscillations. Hence, alternative techniques to provide damping for inter-area oscillations become a necessity for maximum utilisation of power systems.

Since inter-area oscillations are more of a wide-area phenomenon, wide-area signal measurements provided by WAMS can be utilised to provide appropriate remote signals to optimally located damping devices, such as PSS or FACTS (Flexible AC Transmission Systems) controllers, to damp the oscillations. Thus, allowing maximum utilisation of interconnections without violating stability, security and reliability constraints. Applications of WAMS for control of power system oscillations can be categorised based on three control design techniques which are [18]:

- De-centralised controllers
- Centralised controllers
- Multi-agent controllers

A further discussion of these techniques is provided in chapter 3.

2.2.3. Monitoring and Recording

Keeping an eye on power systems, by constantly monitoring the changes in their operating conditions, is an important task for operation and control of such highly non-linear dynamic systems. The implementation of PMU/WAMS technologies in power systems significantly improves the possibilities for monitoring and managing power system dynamics [1, 15]. PMUs installed in selected locations of a power system provide important information about different system states, such as voltages, currents, active and reactive powers, all of which are timely-stamped based on GPS time reference signals. The dynamic system view obtained by WAMS provides improved monitoring capabilities that allow system operators to utilise the existing power systems more efficiently. Improved information about systems conditions allows fast and reliable emergency actions, which reduce the need for relatively high transmission margins required by potential power system disturbances.

Besides the improvement in the monitoring and recording of power system dynamics, WAMS enables the improvement of the task of state estimation [1]. The inaccuracy and delays of traditional SCADA systems can be eliminated by PMU/WAMS based systems. The accurate time-stamped data provided by PMUs can be used as the basis for improved state estimations; thus, allowing instant calculations of system states. Based on fast, accurate and reliable state estimation, a variety of online system stability indices regarding different stability phenomena can be made available for system operators. As a result, the task of optimised operation of existing power systems can be fulfilled.

The focus of this research project will be on the application of WAMS technologies in the area of power system control. The aim is to develop control schemes that are based on WAMS techniques so as to enhance the performance of power systems and allow higher amounts of power transfer across transmission interconnections. In the next chapter one of the rising concerns, which is believed to cause limitation in the amount of power transfer across transmission lines in interconnected power systems, is addressed. These concerns are related to the issue of power system oscillations and their impact on the stable operation of power systems.

2.3. Summary

An overview of wide-area measurement systems (WAMS) and their applications in power systems is introduced in this chapter. The basic elements and architecture of WAMS are illustrated indicating their advantages over traditional measurement and monitoring tools in the form of RTU/SCADA systems. A general view of WAMS applications in the area of monitoring, protection and control of power systems is introduced. The application of WAMS in power system control is the focus of the rest of the chapters of this thesis. In the next chapter (chapter 3), the main focus is power system oscillation and the applications of wide-area based control damping measures.

Chapter 3: Power System Oscillations and Control Measures

3.1. Overview

Power system oscillations are phenomena inherent to power systems. They are often referred to as electro-mechanical oscillations that occur between interconnected synchronous generators in multi-machine power systems [19]. Historically, oscillations in power systems were observed as soon as synchronous generators were interconnected via transmission networks to provide electrical power to remote areas that have no generation capabilities. Interests in interconnecting power system utilities through transmission networks started in the 1950s and 1960s after realising the possibilities of achieving reliability and economic benefits. However, in many cases, high amounts of power transfer across the transmission networks were constrained because of low frequency growing oscillations that are initiated by changes in the operation conditions of power systems [20]. The stability of these oscillations is a compulsory requirement for stable and secure operation of power systems.

As mentioned in section 2.2, to provide effective control strategies, it is important to classify operation difficulties and problems encountered by power systems into physical phenomena so that they can be mitigated and, hence, controlled and counteracted. The phenomenon of power system oscillations is classified, according to the IEEE/CEGRE Joint Task Force on Stability Terms and Definitions [6], as small signal generators' rotor angle stability. This category of stability is concerned with the ability of power systems to maintain synchronous operation following small changes in their operation conditions and it is, in most cases, a problem of insufficient damping of low frequency oscillations [21]. The phenomenon is further broken down into two modes of oscillations; one is of a local nature, whereas the other is of a global or wide-area nature. These modes are:

- Local Modes of Oscillations: These modes are associated with the oscillation of a single generator or a single plant in the power system with respect to the other generators in the system. The oscillation frequencies of these modes are in the range of 0.7 to 2.0 Hz [19],[21]. The characteristics of these oscillations are observable by local measurements of local area states where oscillations occur. In practice, effective control measures that are relatively simple can be developed to damp these oscillations. A typical control measure is a conventional Power System Stabiliser PSS that provides supplementary control signal to generators' excitation systems. The effect of the control signals provided by PSS may be sufficient enough to solve the problem and provide proper damping for the local oscillations.

- Inter-Area Modes of Oscillations: These modes are associated with the oscillation of groups of generators or groups of plants against other groups. The oscillation frequencies of these modes are in the range of 0.1 to 0.8 Hz [19],[21]. The characteristics of these modes are complex and far more different from those of local oscillations modes. The effectiveness in damping these types of oscillations is limited because they are not as highly observable and controllable in local system information as those of local modes. Inter-area oscillations are global problems caused by the interactions among large groups of generators and can have a widespread effect. The absence of a global view of the entire system makes it difficult for local controller, which are effective in damping local oscillations, to provide adequate damping for inter-area oscillations.

In today's power systems and from an operation and control point of view, inter-area oscillations seems to be the most problematic stability aspect due to increasing interconnections between utilities. With increased pressure on utilities to maximise the use of their existing networks and push more power through the interconnections, rising concerns about inter-area oscillations form a challenging barrier that can prevent utilities from achieving such goals. Hence control schemes that overcome this issue and provide proper damping for these oscillations are desirable.

3.2. Wide-Area based Control Schemes for Power System Oscillations Damping

As mentioned in chapter 2 section 2.2, the applications of wide-area measurement systems for wide-area based stability control are realised by three categories of controllers' design philosophies which are; decentralised controllers, centralised controllers and multi-agent controllers. The aim of the three categories is providing tools by which power systems are operated in such a way where system stability is retained and system oscillations are damped properly. Further discussion of these control strategies and an investigation of a number of techniques that have been developed based on these control strategies are included in the following subsections.

The basic structure of decentralised and centralised control schemes is shown in Figure (3-1) bellow [22]. The green part illustrates the traditional framework of decentralised controllers whereas the red part shows that of centralised control strategies. The basic structure of multi-agent based controllers is shown later in Figure (3-6) [22].

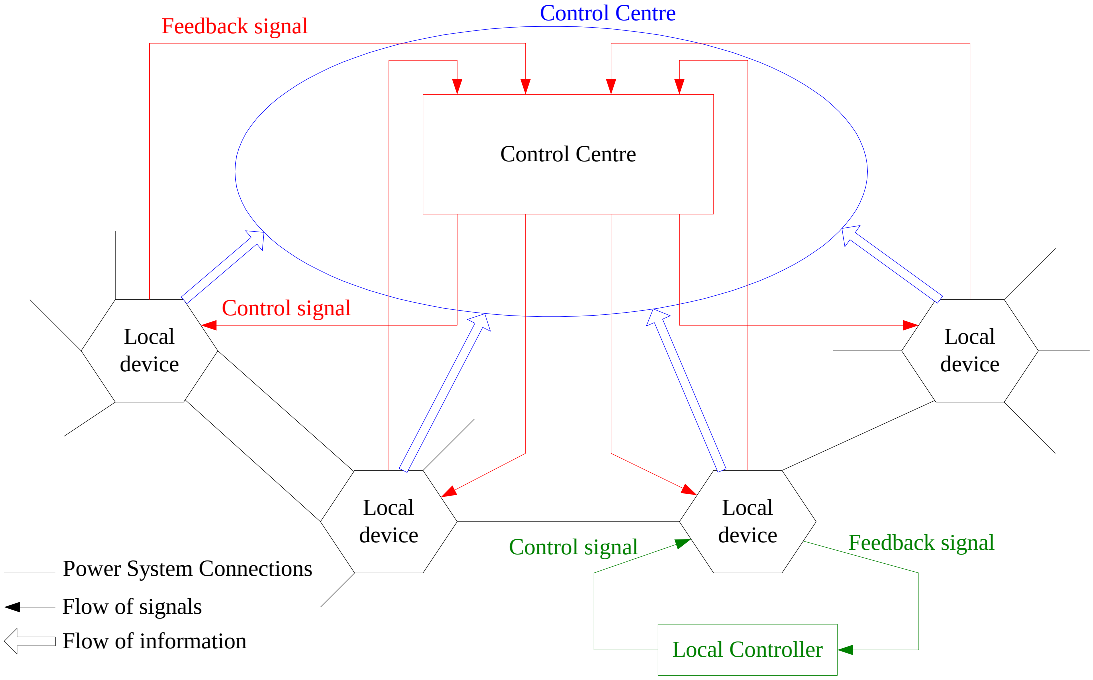

Figure 3-1: Framework of centralised and decentralised control schemes [22]

3.2.1. Decentralised Control Strategies

The function of decentralised control schemes is realised by local controllers that are installed to act upon local devices and provide control actions to alter the status of these local devices to meet the requirement of the specific operation condition (as shown by the green part in Figure (3-1)). Traditional decentralised controllers are designed based on locally available feedback signals that provide direct information about the local devices to which these controllers are connected. The local feedback signals are processed by the controller and based on the objective function of the controller, control signals are determined and sent to the local device to adjust its operational status. The drawbacks of these traditional schemes is that the actions of the local controllers consider only the status and requirement of the local devices and do not take into account the status and needs of other local devices in the network. Considering that, in many cases the requirement of other local devices can be significantly influenced by the action of a local controller, it is clear that under such schemes of decentralised controllers the effectiveness of local controllers is constrained. An improvement of such schemes can be made if decentralised controllers are designed so that they can have a wider view of the system status and be able to support each other. WAMS applications in this area provide the required tools to improve the performance of these local decentralised control schemes. Such an improvement can be made possible by providing additional global and remote signals to the existing local controllers. Hence, global phenomena such as inter-area oscillations can be counteracted more effectively.

Interests in enhancement damping capabilities of local decentralised controllers based on global signals started in 1990s. A good example of this is the proposed method introduced in reference [23]. The proposed controller is, basically, a two level Power System Stabilizer PSS. The objective function of the first level of control is to damp the local mode in the area where the controller is installed using generator rotor speed signals as a local feedback input signals to the controller. The objective function of the second level of control is to provide damping for inter-area oscillatory modes using additional global feedback signals. Two types of global feedback signals are suggested; tie-line active power and speed difference signals. Location of the two level PSS, input signals selection, and tuning of the controller parameters are obtained based on modal analysis techniques using participation factors or transfer function residues. In the same research, the same principles of two levels of control are also applied to SVC (Static VAR Compensator) devices located in the middle of the transmission line connecting two oscillating groups. The two level PSS is shown in Figure (3-2).

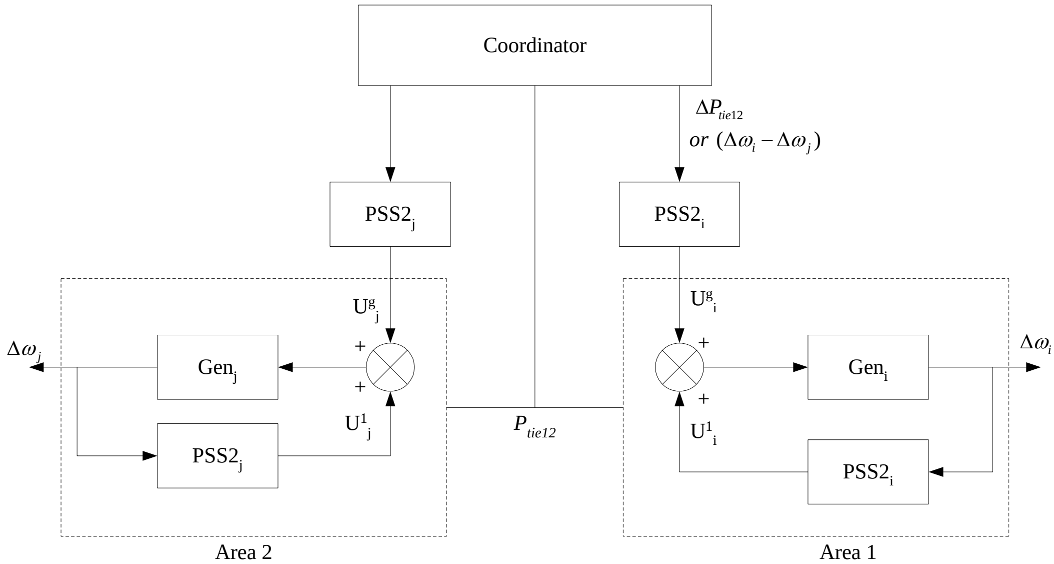

Figure 3-2: Two-level PSS design architecture [23]

Reference [24] adopts a decentralised / hierarchical approach to design a wide-area signal based PSS that provides the required additional damping for inter-area oscillation modes in the Hydro-Quebec's transmission system. The design approach uses the state space system identification techniques. Once the state space model of the system is obtained, observability and controllability measures are computed from which PMUs remote signals spread over coherent areas are selected. Again, the proposed PSSs in this research have two control levels. The first is a traditional speed sensitive local loop operating in the traditional way [17] whereas the second level is a WAMS based global loop that uses a single differential frequency signals between two selected areas. Since the remote feedback loops are built on top of an existing decentralised control system, the design approach, therefore, results in a decentralised / hierarchical structure. The general architecture of the control system is shown in Figure (3-3).

A methodology to compare wide-area and local signal based supplementary control of shunt FACTS devices for improved damping of inter-area oscillation modes is presented in [25] through numerical simulations of a three-area test system and generalised on a large study system using a revised Hydro-Quebec network. Again, the results suggest that wide-area based damping controllers have obvious advantages. However, it also suggest that local control can be quite effective even at moderate gains and, therefore, it is recommended that in a decentralised / hierarchical design approaches, one should always start with local control loops and then add wide-area control loops as needed, depending on the system requirements.

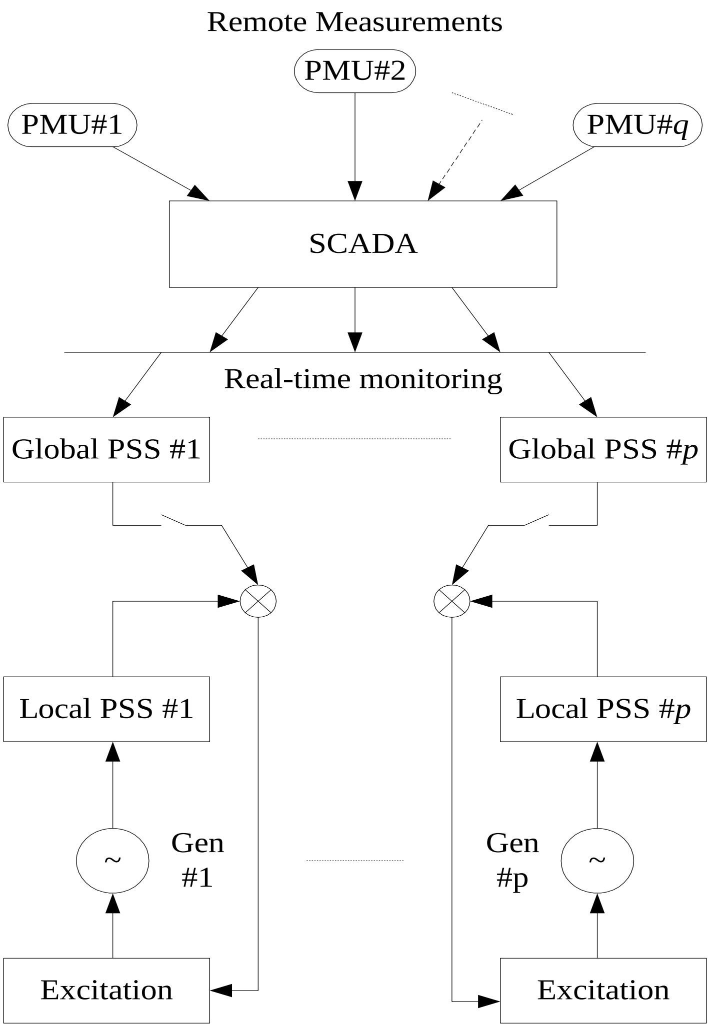

Figure 3-3: General architecture of a decentralised / hierarchical PSS design [24]

Test results for the aforementioned attempts show that a major improvement in the stability of power systems using wide-area measurements as an additional input signals for decentralised damping controllers can be achieved. However, focus needs to be put when designing such wide-area based controllers regarding signals transmission time delays as time delays, if not considered in the design process, can have a significant impact on the system stability.

3.2.2. Centralised Control Strategies

The function of traditional centralised control schemes is realised by centralised controllers which are located in control centres. A centralised controller receives feedback signals from all local devices in a power system and sends control commands to these devices (as shown by the red part in Figure (3-1) above). This indicates that a large amount of information is needed to be transmitted to the control centres where this information is processed and then control measures are taken. Hence a significant time-delay is involved, which implies that traditional centralised control methods applied to power systems are for the control of slow process and are not suitable for fast on-line power systems control. The advantages of WAMS in providing fast transfer capabilities of synchronised measurements open a new path by which centralised control can be enhanced significantly. Examples of attempts to do so are described briefly next.

A two level hierarchical structure is introduced in [26] to improve the stability and oscillation damping in multi-machine power systems. The proposed structure consists of a local controller for each generator at the first level helped by multivariable central controller at the secondary level. The secondary-level controller uses remote signals from all generators to produce decoupling control signals that improve the performance of the local controller. The local controller uses only local signals to damp local oscillation modes. The proposed hierarchical controller structure is shown in Figure (3-4).

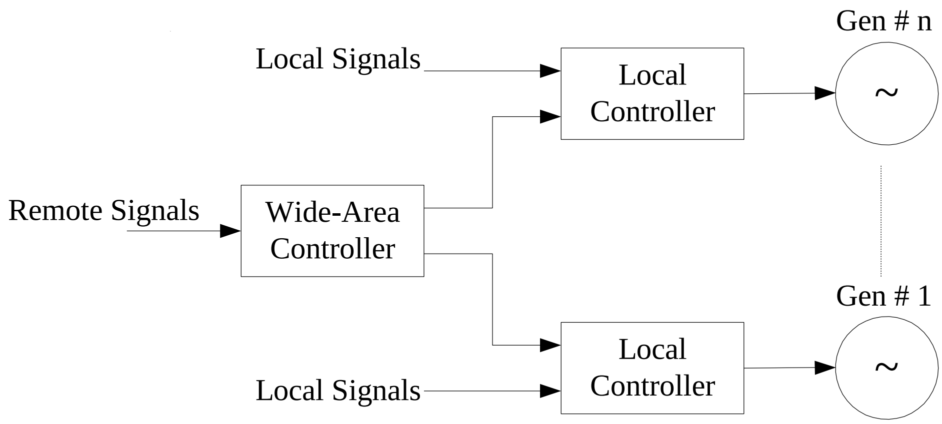

Figure 3-4: The hierarchical controller structure [26]

In the proposed scheme, problems of voltage regulation and rotor oscillations damping are addressed simultaneously. The second-level controller continuously adapts its parameters through a gain scheduling algorithm and provides additional control signals to local controller based on wide-area system view. In the absence of the global signal from the centralised wide-area controller, local controller still can perform in a traditional way. Test results show that the performance of local controllers is considerably enhanced by the secondary control action and system stability is improved in presence of severe operating conditions.

A centralised control system for damping power system inter-area oscillation using wide-area measurement is presented in [27]. Again, the proposed scheme consists of two levels of control. The first level is fully decentralised and consists of conventional PSSs. The second level is centralised and provides supplementary damping signals that are sent to local devices in addition to the first level of control. The general structure of the centralised wide-area damping control system is shown in Figure (3-5).

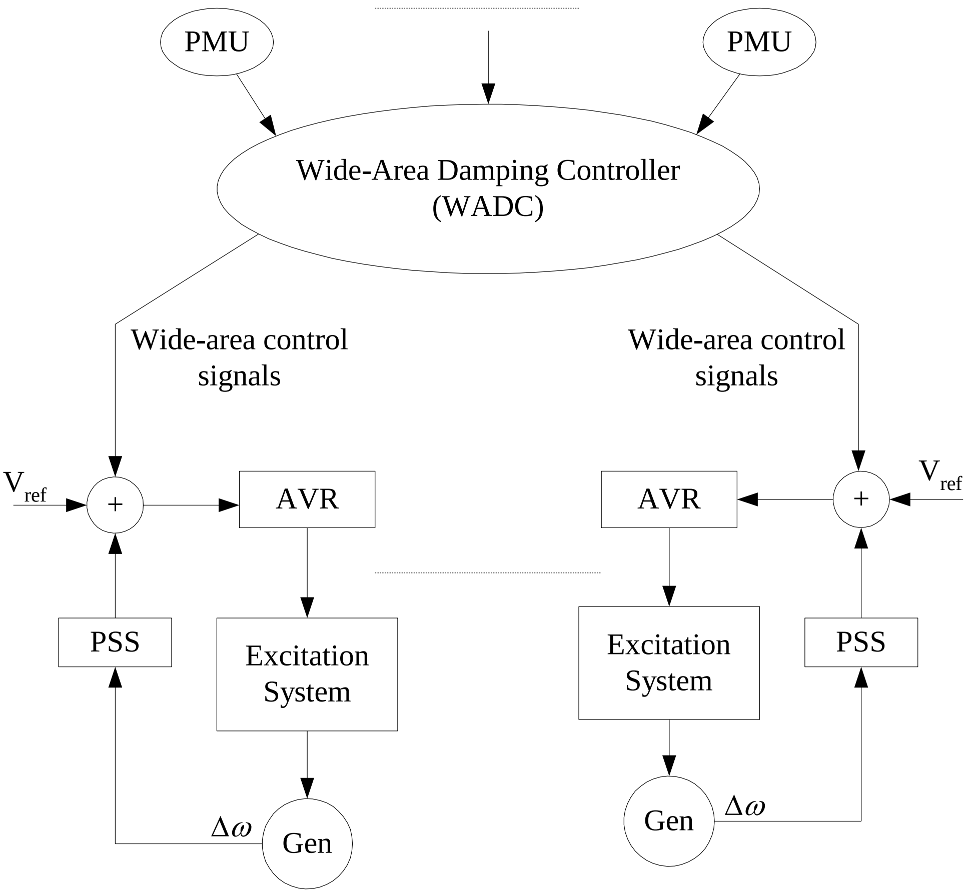

Figure 3-5: General structure of a wide-area centralised damping control system [27]

In the proposed scheme, geometric measures of controllability/observability are used to select the most effective stabilizing signals and control locations. Line power flows and currents are found to be the most effective input signals to the controller. The application of Linear Matrix Inequalities (LMI) is used for tuning and optimisation of the controller. The test results show that the use of linear, continuous methods to design a controller, although very powerful, requires a considerable tuning, testing and further development when implemented in nonlinear discontinuous real systems such as power networks. However, the designed controller shows promising results in providing effective damping for power system oscillations as well as obtaining robust control performance.

A multiple-input, single-output (MISO) controller is designed in [28] for a Thyristor-controlled series capacitor (TCSC) to improve the damping of inter-area oscillation mode in power systems. The stabilising signals are obtained from remote locations based on observability of critical inter-area oscillation modes. The design of the centralised controller is formulated as a multi-objective optimisation problem in the LMI (Linear Matrix Inequalities) framework. Using both, Eigen values analysis and time domain simulation, the robust performance of the proposed controller has been verified. It concluded that, because the number of inter-area oscillation modes in practical power systems is often much larger than the number of available control devices, centralised control design approach using global signals is, therefore, one of the potential options for stability enhancement and utilisation improvement.

3.2.3. Multi-agent Control Strategies

Coordination of control measures taken by multiple decentralised local controllers is a significant task that can play a significant role in the enhancement of the overall performance of modern power systems. Most decentralised control schemes exist today; however, rely on non-adaptive coordination techniques that are determined by off-line coordination methods. Such techniques do not consider on-line changes in the operating conditions of power systems. As a result controllers lack the ability to adapt to the variations of power system operating conditions and, therefore, are unable to function effectively under unexpected circumstances. With the rising complexity of power systems, there are needs to utilise these local controllers more efficiently. Hence, more effective coordination between decentralised local controllers is desirable. Coordination should rely on on-line exchange of information in such a way that controllers support each other and take into consideration the status of other nearby devices, instead of focusing their control actions only on the status of local devices. Such coordination techniques have the advantages of flexibility, autonomy intelligence and on-line adjustment capability, all of which can be applicable by the applications of multi-agent technology in the area of power system operation and control [29],[30]. General framework of multi-agent based coordinated controllers is shown in Figure (3-6) [22].

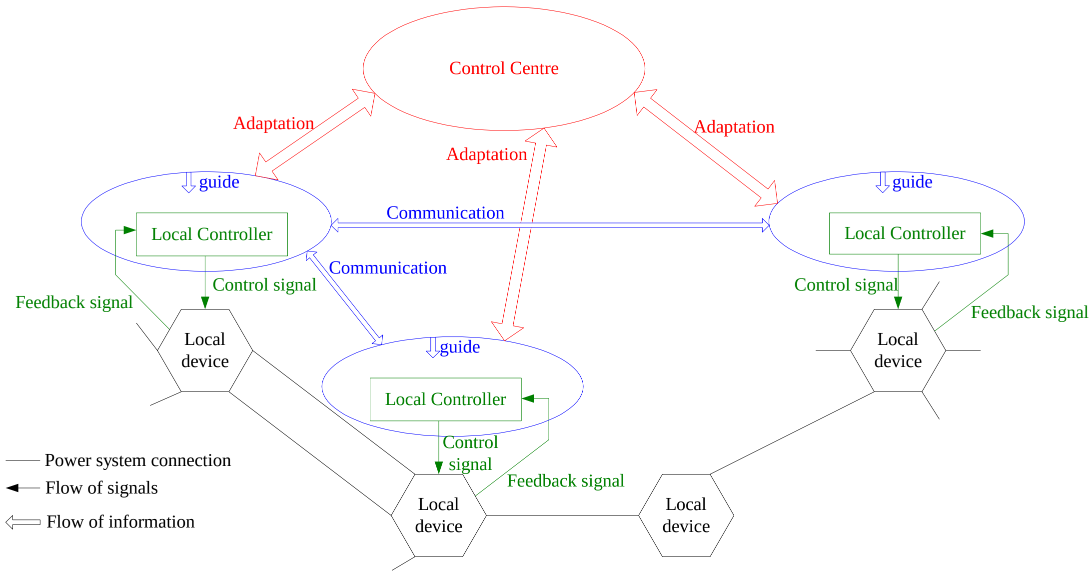

Figure 3-6: Framework of multi-agent based controllers [22]

Reference [31] proposes a supervisory level power system stabiliser (SPSS) using wide-area measurements. The coordination between the proposed SPSS and the local Power system stabiliser (LPSS) is implemented based on the concept of multi-agent system theory. In the proposed multi-agent damping control scheme, LPSSs are placed at the selected generator excitation loops and tuned to damp local oscillation modes. They are categorised as local agents and remain in the same location throughout their working lives. The SPSS operates as a software agent that has three main components as shown in Figure (3-7). These components are; agent communications, fuzzy logic controller switch and robust control loops. The function of fuzzy logic controller is to switch to the appropriate robust controller to provide a satisfactory damping for the corresponding system operation conditions. The controller embedded in the SPSS control loop is designed based on H_∞ controller using selected wide-area measurements. The use of H_∞ optimization method to design the controller is adopted to accommodate power system nonlinear dynamic performance and model uncertainty.

The additional damping signals produced by the SPSS are sent to local machines to provide damping for system oscillation through the excitation systems of these local machines as shown in Figure (3-8).

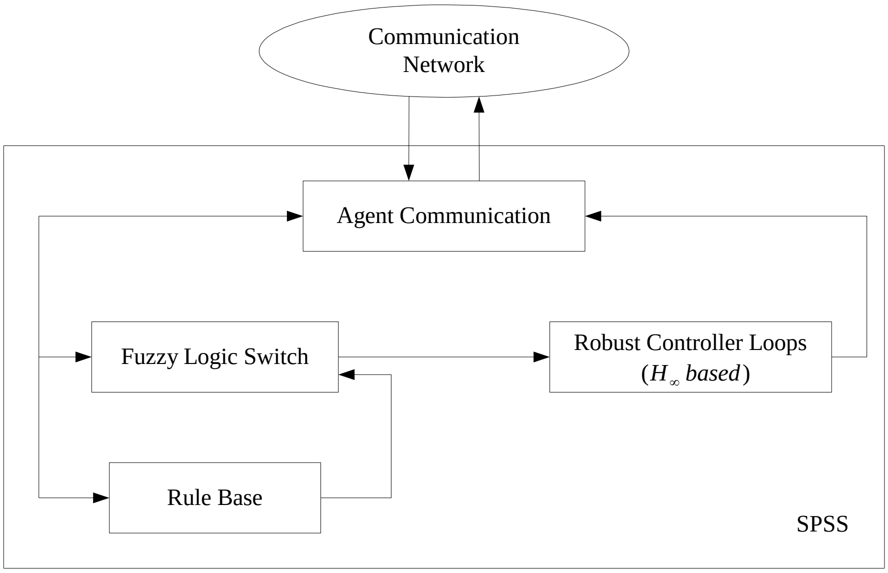

Figure 3-7: Components of SPSS [31]

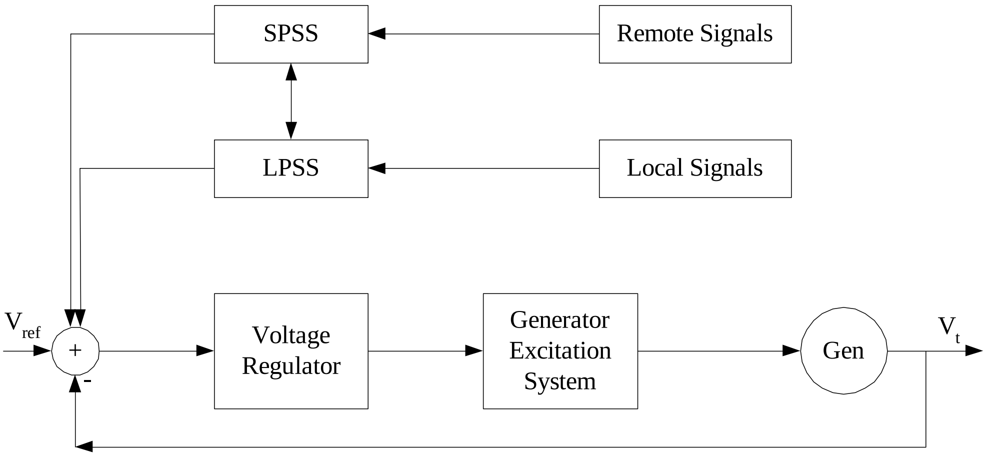

Figure 3-8: Conceptual input/output scheme of SPSS [31]

In the proposed techniques signal transmission delays are not taking into account. Also the control loops design is determined off-line which may cause issues when the operating conditions change significantly. Nonetheless, the test results of the technique show that the proposed design can effectively damp system oscillations under range of operating conditions.

3.3. Power System Oscillations and the Concept of Coherent Clusters

As discussed in section 3.1, electromechanical oscillations are inherent phenomenon to power systems that is highly related to the complex dynamics of highly non-linear systems. However, the frequency of these oscillations and the number of synchronous machines involved in any electromechanical oscillatory mode depend on the structure of the power system network. Generally speaking, low frequency electromechanical oscillations are more likely to be observed when geographically dispersed generation/load areas are connected to each other via relatively weak transmission lines compare to the rest of the transmission network [32]. The weak interconnections can, sometimes, be obvious when, for example, two independent power system networks are interconnected through a single tie-line. However, for systems which have been interconnected for a period of time, electromechanical oscillations may appear due to stressed operation conditions and increase in power transfer across the transmission network. In such cases, identifying critical transmission lines and critical areas from which oscillatory system behaviour may originate becomes a vital task for stability studies and control of power systems.

Experiences and observations of operation of power systems networks conclude that, when a stressed power system experiences a disturbance or a change in its operation conditions, electromechanical oscillation between interconnected synchronous generators may appear. Following a change in their operation conditions, power systems tend to oscillate coherently with groups of generators in a specific area of the power system behaving coherently in low frequency electromechanical oscillations [20]. Those groups of coherent generators are separated, yet connected, to other groups of coherent generators by weak transmission lines.

These observations bring about the concept of Coherent Clusters or Critical Clusters (CC). A Coherent Cluster of synchronous generators can be defined as the group of generators that behaves similarly or have similar response characteristics to changes in the operation conditions of a power system in which they operate. The identification of these clusters is of importance in the study of power system stability and the design of the appropriate countermeasures that aim to maintain system stability. A number of approaches have been proposed and applied to identify the coherent clusters in multi-machine power systems, some of which are discussed in the next section (section 3.4).

3.4. Identification of Coherent Clusters in Power Systems

Considerable amount of research has been devoted to identify coherent clusters of synchronous generators in multi-machine power systems. Most of these research pieces differ in their approach in how to obtain or identify the coherent clusters. For example, coherency-based approaches have been, in the past, proposed to aggregate those generators in certain coherent groups, which have similar responses to a system disturbance, into dynamic equivalent subsystems for the purpose of developing reduced dynamic equivalents for large interconnected power systems [33],[34],[35]. In these approaches, the coherent group is replaced by a single generator which has dynamic parameters identical to those of each generator in the group, but which has a rating equivalent to the total group rating. Thus, reduced dynamic models for large power systems are obtained. However, from an operation and control point of view, the identification of coherent clusters is of importance for proper understanding to power system stability studies and for the design of control schemes that aim to enhance the overall system performance.

Early research [36] based on the Extended Equal Area Criterion EEAC [37] focuses on splitting the multi-machine power system into two groups of machines; one group forms the critical machines and the other one consists of the remaining machines. The critical machines are those responsible for loss of synchronism in a power system following a disturbance and therefore, coherent in their response to the disturbance. The aim of this approach is to evaluate the system's stability margin corresponding to a given disturbance. A different approach introduced in [38, 39] uses the line transient potential energy to identify vulnerable transmission segments and clusters of critical machines. This approach considers the phenomenon on the power system network rather than the group of machines. The basic concept is that, following the clearance of a fault, the increase in the generator rotors kinetic energy will be converted into potential energy and distributed over the whole network. If the converted energy can be absorbed by the network, the system will remain stable; otherwise instability may occur and there will be a corresponding unstable cut-set. Based on this concept, an index is derived to identify the critical cut-set (critical lines). According to this index, the lines are sorted in ascending order and then removed one by one until an island is formed. This island includes the coherent or critical machines and it identifies the critical clusters.

Giving the advantages of WAMS, identifying coherent clusters of generators based on wide-area signal measurements plays a significant role in the design of wide-area based stability controls. Research aimed to identify coherent clusters based on PMUs measurements has evolved recently, some of which is discussed briefly next.

Reference [40] discusses a way of clustering generators in coherent groups based on phasor measurements obtained by PMUs. The clustering technique uses Discrete Fourier Transform (DFT) analysis for estimated internal voltage phasor of all generators to derive indices that are used to aggregate those generators into coherent groups. A method suitable for real time coherency identification is introduced in [41]. Fourier analysis are applied to the monitored generator speed signals in [41]. The basis of this method relies on the theory that during normal operation of synchronous generators, their rotor speed deviation is zero. During a disturbance, the rotor angle will change to meet the new system condition. This change in the operating point appears as a developed oscillation which can be seen as a speed deviation on the rotor speed signals. Based on these facts and by monitoring the generator speed and applying Fourier analysis, the fundamental speed will be recognised by the zero frequency spectral components while the speed deviation is reflected by the nonzero frequency components. Furthermore, the phases of the dominant nonzero frequency components of all generators are also determined, and by comparing them, the generators coherency can be acquired. Another technique based on wide-area signal measurements is developed in [42]. The method introduces a hierarchical clustering technique of (N) generators into coherent groups based on wide area measurements. The clustering method can produce any number of groups between 1 and N. Then a single generator is selected to represent each group. The rotor frequencies of the representative generators are used to identify the cluster with the largest initial swing; hence, identifying the event location (i.e. finding the most likely group from which an event originates). The method uses a weighted sum squared error (WSSE) objective function to aggregate the generators two clusters at a time starting from each generator as a cluster itself. Choosing which two clusters to merge is based on the well-known Ward’s method.

The main drawbacks of the previously described techniques are that they do not consider wide range of operating scenarios for power system networks. Instead, the identification of the coherent clusters is obtained based on system response to predefined, limited contingencies. Due to the fact that clusters configuration may be significantly influenced by the type, size, and nature of the encountered disturbance, a technique that can take into account as many events that lead to oscillatory behaviour of the machines as possible is desirable. Such clustering technique will assure the accuracy in the clustering configuration for the system regardless of variation in the operating scenarios.

3.5. Summary

The phenomena of power system oscillations and its threatening impact to the stable operation of power systems are presented in this chapter. A number of wide-area based control schemes developed to enhance power system oscillation damping capabilities is reviewed and summarised based on the adopted control strategy (i.e. centralised control strategy, decentralised control strategy and / or multi-agent control strategy). Also the concept of coherent clusters (CC) which is related to the oscillations of coherent groups of synchronous generators in multi-machine power systems is introduced. A number of techniques developed to identify coherent clusters in power systems are summarised in an attempt to identify the drawbacks of such techniques and develop a new algorithm to determine the coherent clusters in large power systems. In chapter 4, a new technique to identify coherent clusters of synchronous generators in multi-machine power systems is proposed. The merits of the proposed method are the following:

- ➢ The clustering technique is based on wide-area signal measurements; hence it is suitable for implementation in WAMS based monitoring and control system.
- ➢ A new technique is proposed to account for the effect of different types of events on the clusters configurations. Thus, the accuracy in the clustering is assured.

Chapter 4: A Novel WAM based Technique to Identify Coherent Clusters in Multi-machine Power Systems

4.1. Overview

The Coherent Clusters are previously defined as the groups of generators that behave similarly or have similar response characteristics to changes in the operation conditions of a power system in which they operate. Changes in the operation conditions of a power system may, sometimes, cause oscillations of groups of generators against other groups. The oscillations characteristics are highly observable in generators rotor signals such as generators rotor speed deviation signals or generator rotor angle signals. If quantities that describe the dynamic behaviours of generator rotors during system oscillation are available, coherency measures can be derived to identify the coherent clusters.

Recent research suggests that generator rotor angle measurements can be obtained using Phasor Measurement Units (PMUs) technologies [42],[43],[44]. Therefore synchronised measurements of generator rotor frequencies using a wide-area measurement system are applicable. Hence an algorithm that identifies coherent generators based on these measured quantities can be implemented in a wide-area based stability control scheme. In this section, an agglomerative hierarchical clustering algorithm is proposed to group any number of generators in a given multi-machine power system into coherent clusters based on simulation data. The clustering is based on coherency measures obtained from the time-domain responses of all generators following a disturbance. The main advantage of this proposed method over the other previously described wide-area based methods lies in the proposed technique introduced to account for as many events that lead to oscillatory behaviour of the machines as possible. Thus it is assured that the obtained cluster configurations are the most likely ones to be formed under any type of disturbances.

4.2. Methodology

The proposed agglomerative hierarchical clustering algorithm is to be applied for a data set consisting of the time-domain responses of all generators during and following a disturbance. A typical time domain response of a group of interconnected synchronous generators to a disturbance or a change in the operation conditions of the power network is similar to the one shown in Figure (4-1) bellow. The dynamic quantities being observed in Figure (4-1) are the rotors' speed deviation signals following a system disturbance. As can be seen, prior to the event, speed deviations of all generator rotors are Zeros indicating stable operation of the generators where electrical power is being delivered at constant rotor speeds and constant rotor angles. Following a disturbance, the rotor angles move to meet the new operating condition. These changes in the operating points result in developed oscillations which can be seen as speed deviation on the rotors' speeds. The oscillations continue for a period of time and then decay, if there are enough damping forces in the system.

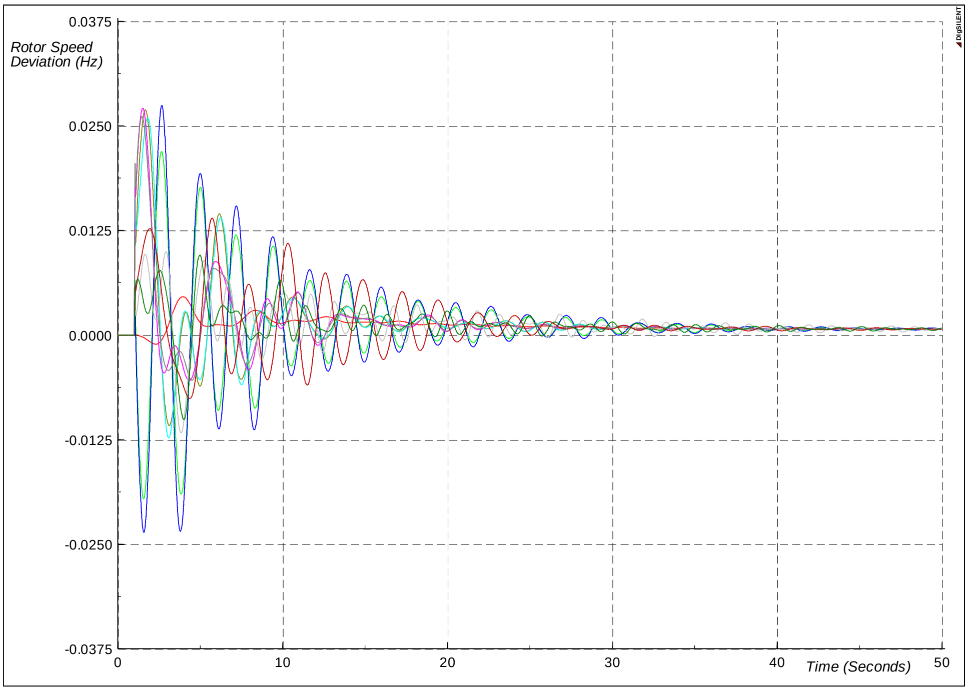

Figure 4-1: Typical response of generators group (rotors speed deviation) to a system disturbance

Considering a system consists of (N_g) generators, the generators' rotor speed deviation ($\Delta\omega$) can be taken as the basic time-series data set to represent the dynamics of all the generators in the power system. For a given disturbance or event (*e*) and for a response time (*T*), the data set to be clustered can be presented by the following matrix.

$$\Delta\omega_e = \begin{bmatrix} \Delta\omega_1(t_1) & \Delta\omega_1(t_2) \,\ldots\ldots\ldots\, \Delta\omega_1(t_T) \\ \Delta\omega_2(t_1) & \Delta\omega_2(t_2) \,\ldots\ldots\ldots\, \Delta\omega_2(t_T) \\ \vdots & \vdots \\ \vdots & \vdots \\ \Delta\omega_{N_g}(t_1) & \Delta\omega_{N_g}(t_2) \ldots\ldots\, \Delta\omega_{N_g}(t_T) \end{bmatrix} \tag{4.1}$$

Where:

$\Delta\omega$: is the rotor speed deviation.

T: is the time of the event simulation.

N_g: is the number of generators.

From such a data set, coherency measures between generators can be identified.

4.2.1. Coherency Identification

From the data set matrix, coherency between each pair of generators can be obtained by computing the Euclidean Distance [45] for each pair, as in equation (4.2). The Euclidean distance reflects the dissimilarity between each pair of generators in their response to the encountered disturbance. And for this reason, it will be referred to as the dissimilarity coefficient.

$$d_{ij} = \sqrt{\sum_{t=t_1}^{T} (\Delta\omega_i(t) - \Delta\omega_j(t))^2} \tag{4.2}$$

Where:

d_{ij}: is the dissimilarity coefficient between generator i and generator j.

$\Delta\omega_i(t)$: is the i^{th} generator speed deviation at the time instant (t).

$\Delta\omega_j(t)$: is the j^{th} generator speed deviation at the time instant (t).

Based on dissimilarity coefficients matrix obtained by (4.2), the pairs with the smallest distance are selected to be merged into one cluster. Then the dissimilarity matrix is updated by calculating the distances between the new clusters. Various clustering techniques differ in how to update the dissimilarity matrix. Hierarchical agglomerative clustering techniques are integrated into MATLAB and there are different methods available to compute the updated dissimilarity matrix. The average linkage method is one of the methods with the best performance and it uses the average distance between all pairs of objects (generators in this case) in any two clusters as in equation (4.3):

$$d_{rs} = \frac{1}{N_r N_s} \sum_{i=1}^{N_r} \sum_{j=1}^{N_s} dist\left(x_{ri}, x_{sj}\right) \tag{4.3}$$

Where:

d_{rs} : is dissimilarity coefficient between cluster (*r*) and cluster (*s*).

N_r and N_s : are the number of objects (generators) in cluster (*r*) and (*s*) respectively.

$dist\left(x_{ri}, x_{sj}\right)$: is the distance between object (x_i) in cluster (*r*) to object (x_j) in cluster (*s*).

4.2.2. The Events' Effect on the Clustering

It is well established that the response of a generator to a disturbance depends on the type of event or disturbance (i.e. multi-phase/single phase fault, line trip, event of load, etc.) as well as on the location of the event. Therefore, the clustering process may be influenced by the configuration of events. It is also well known that the machine inertias are typically proportional to the active power output of the machine [46]. If the generators' active power output during an event disturbance is available, the influence of that specific event can be taken into consideration. Generators' active power outputs also follow a pattern of oscillation behaviours following a system disturbance similar to those shown in Figure (4-1) for the speed deviation. A typical response is similar to the one shown in Figure (4-2) which shows active power outputs of group of generators following a system disturbance.

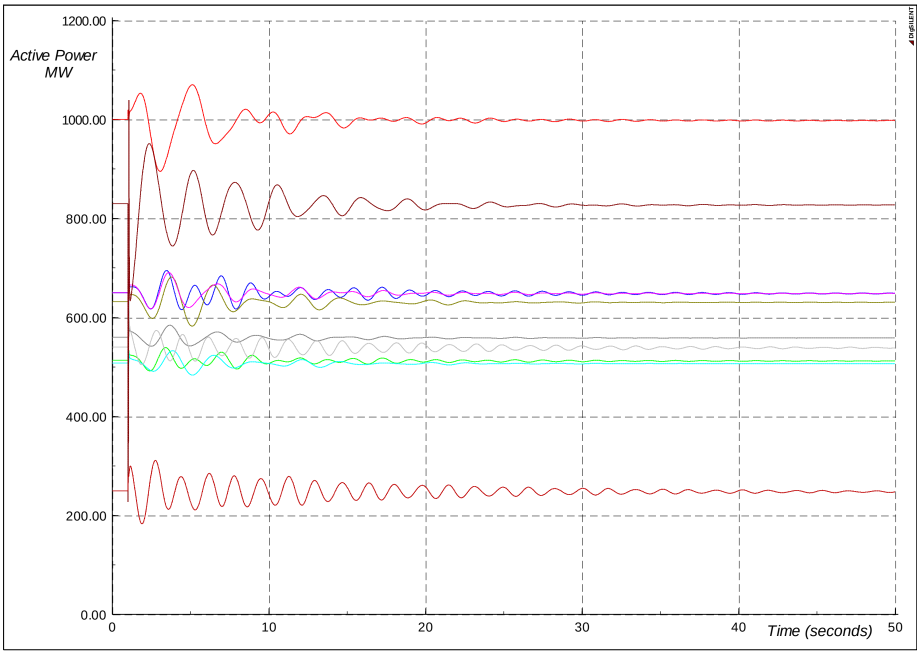

Figure 4-2: Active power outputs of generators group during a system disturbance

Equation (4.1) gives a time-series data set that describes the responses of (N_g) generating unit to a specified event (e). For the same event, a time-series matrix of generators' active power output can be obtained from the time domain simulation for the same time period (T), as in equation (4.4).

$$P_e = \begin{bmatrix} P_1(t_1) & P_1(t_2)\,\ldots\ldots\ldots\, P_1(t_T) \\ P_2(t_1) & P_2(t_2)\,\ldots\ldots\ldots\, P_2(t_T) \\ \vdots & \\ \vdots & \\ P_{N_g}(t_1) & P_{N_g}(t_2)\ldots\ldots P_{N_g}(t_T) \end{bmatrix} \tag{4.4}$$

Equations (4.1) and (4.4) are the time-series matrices of generators' speed deviation and active power output, respectively, for a specific event (e). For a number of events (m), an equivalent data set for the speed deviation matrix can be computed taking into account the weight of each event by considering the active power output of each generator during each event. The speed deviation of the (i^{th}) generators at the instant of time (t) can be computed as an equivalent, considering all events, as follows:

$$\Delta\omega_{eq}^{i}(t) = \frac{\sum_{e=1}^{m} \Delta\omega_{e}^{i}(t)\, P_{e}^{i}(t)}{\sum_{e=1}^{m} P_{e}^{i}(t)} \tag{4.5}$$

Where:

$\Delta\omega_{eq}^{i}(t)$: is the equivalent speed deviation of the i^{th} generator at time (t).

$\Delta\omega_{e}^{i}(t)$: is the speed deviation of the i^{th} generator at time (t) for the event (e).

$P_{e}^{i}(t)$: is the active power output of the i^{th} generator at time (t) for the event (e).

m : is the number of events.

The equivalent speed deviation data set matrix is shown in equation (4.6). The data set included in this matrix is then used in the clustering algorithm to compute the dissimilarity matrix and to form the cluster tree, equations (4.2) and (4.3).

$$\Delta\omega_{eq} = \begin{bmatrix} \Delta\omega_{eq}^{1}(t_1) & \Delta\omega_{eq}^{1}(t_2)\ldots\ldots\ldots\Delta\omega_{eq}^{1}(t_T) \\ \Delta\omega_{eq}^{2}(t_1) & \Delta\omega_{eq}^{2}(t_2)\ldots\ldots\ldots\Delta\omega_{eq}^{2}(t_T) \\ \vdots & \\ \vdots & \\ \Delta\omega_{eq}^{N_g}(t_1) & \Delta\omega_{eq}^{N_g}(t_2)\ldots\ldots\Delta\omega_{eq}^{N_g}(t_T) \end{bmatrix} \tag{4.6}$$

Using equations (4.1) to (4.6) the clustering algorithm used to group the power system synchronous generators into coherent clusters is described by the flow chart in Figure (4-3).

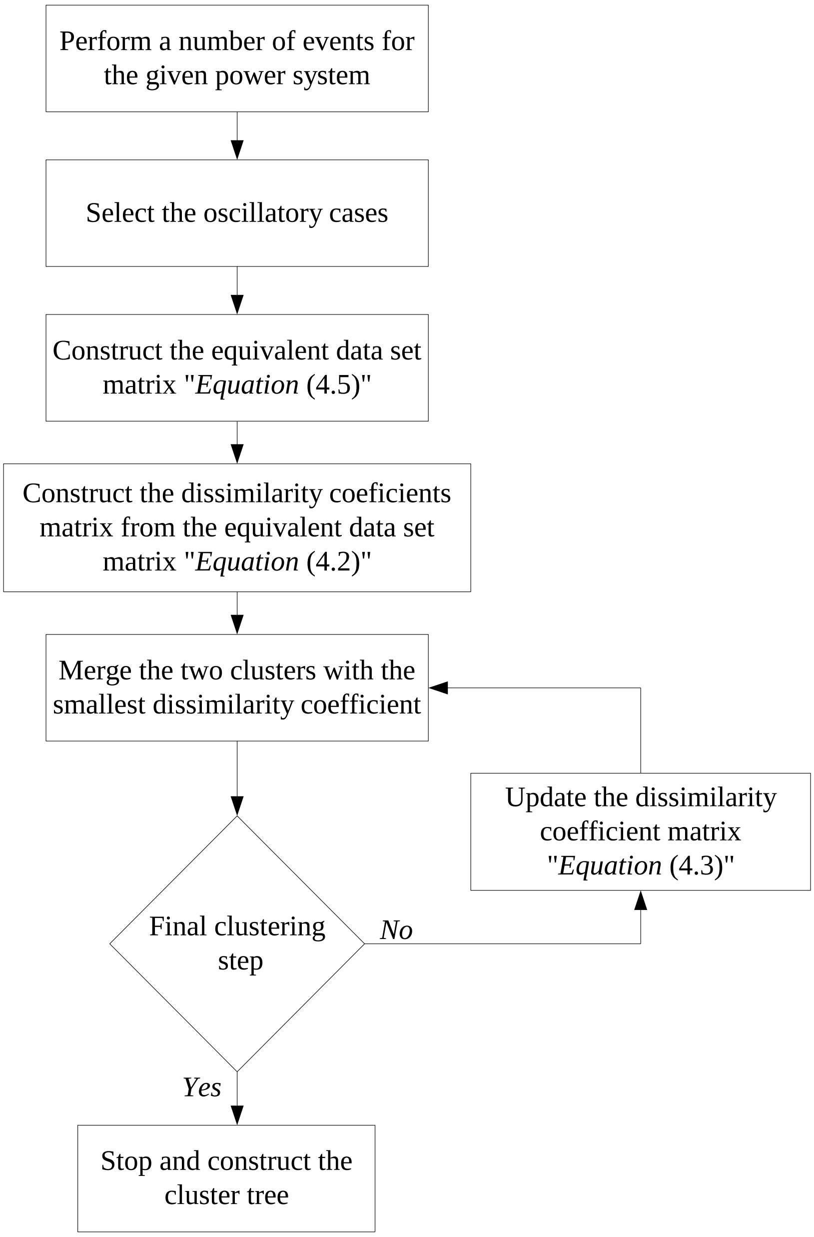

Figure 4-3: Flowchart for the proposed clustering algorithm

4.3. Algorithm Implementation (Software and Simulation)

To acquire the measurements needed by the proposed clustering algorithm, the DIgSILENT (*Digital Simulator for Electrical Network*) simulation software is used to simulate the power system under study. DIgSILENT [47] is a consulting and software company based in Germany that provides specialised services in the field of electrical power systems for transmission, distribution, generation and industrial plants. The software is an integrated power system analysis tool that combines reliable and flexible system modelling capabilities. It has the capabilities of simulating an arbitrary power system network on every time scale, from steady state load flow analysis through to electromagnetic transient simulation. DIgSILENT provides a basic simulation kernel, which together with a comprehensive model library and graphical user-definable modelling system, provides an extremely flexible and powerful platform for solving power system dynamic problems. Simulation functions available in DIgSILENT includes; load flow and fault analysis of complete AC/DC network representation, low voltage network analysis, distribution network optimisation, electromechanical dynamic simulation, electromagnetic dynamic simulation, Eigen value analysis, protection analysis, harmonic analysis, reliability analysis, voltage stability analysis, contingency analysis, power electronic device modelling, and others [47]. In addition, it has a wide range of built-in detailed and dynamic models of power systems equipment and controllers including synchronous/asynchronous machines, transformers, excitation systems and voltage regulators AVRs, generators speed governors, power system stabilisers, DFIG and full converter wind turbine, etc, all of which make it a very attractive package for usage.

4.4. Test Systems

Test systems are widely used in power system research studies. There are reasons for using such test systems instead of using models of practical systems such as the following:

- Scarcity of practical power systems data due to confidentiality.
- Dynamic and static data of the systems are not well documented.
- Due to the large set of data of real world power systems, calculations of numerous scenarios can be very difficult.
- Lack of software capabilities for handling large set of data. Most educational softwares have limitations regarding system sizes.
- Results from practical power systems are less generic due to the special arrangements and specific standard for each practical system. Whereas standard test systems are more generic and mimic the behaviours of real system to a certain extent.

For these reasons, a number of standard test cases are documented for research purposes. The available test cases and commonly systems can broadly be categorised into transmission test system, distribution (sub-transmission) test systems and unbalanced distribution systems. In this research work, test systems which are suitable for studies of power system stability, low frequency oscillatory stability analysis and studies of new controllers in power system stability are used. For testing the coherency identification algorithm two standard test systems are used as case studies. Those test systems are the 16 generator 68 bus test system and the IEEE 39 bus test system.

4.4.1. Case Study 1: 16 generator 68 bus test system

The study system used to test the performance of the proposed algorithm is the standard 16 generator 68-bus system which is a reduced order equivalent model of the New England / New York interconnected power system. In this system, there are 68 buses and 16 generation units, interconnected via high voltage transmission lines. The single line diagram of the system is shown in Figure (4-4). Generators G1 to G9 are in New England whereas generators G10 to G13 are in New York. Generators G14, G15 and G16 are equivalent generators in neighbour areas of New York. The system has so far been widely used in research work for the studies of power system stability and control related issues. It is highly recommended in the study of inter-area oscillations in power systems and in finding coherency property between synchronous generators in multi-machine interconnected power systems [20].

The system is modelled using the dynamic simulation programme DIgSILENT (*Digital Simulator for Electric Network*). All generation units are equipped with excitation systems and speed governors control. The system detailed data can be found in [20] and are also included in Appendix A1.

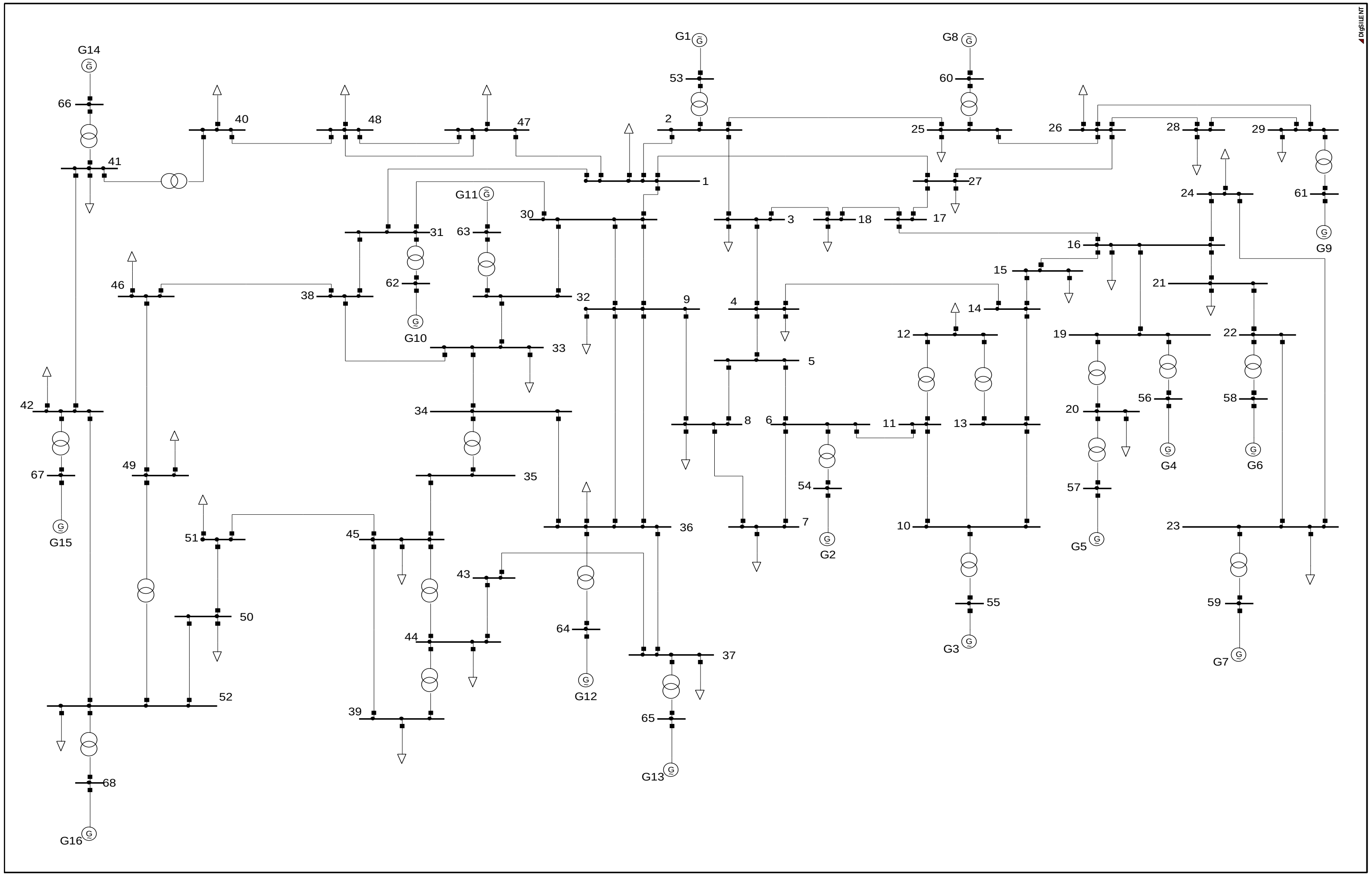

Figure 4-4: The 16 generator 68 bus test system

A. *Events Configurations*

For the algorithm to be effective in identifying coherent clusters of generators, a wide range of possible contingencies that may occur in any realistic power system has to be considered. For the study system used in this study, all possible line outages are considered. This is to ensure that all generators are included in the clustering (i.e. no generation outages are considered) and the fact that transmission line outages due to faults are the most credible events that could lead to system oscillations. For the study system, there are 62 transmission lines; therefore 62 transmission line outages are simulated as follows:

For each line, a three phase fault is applied at 50% of the line length which leads to a permanent disconnection of the faulted line. The fault occurs at 1 sec and is cleared by line tripping within 90 msec. The simulation time is 50 sec. The process of line outages is automated using DIgSILENT simulation software. For each contingency the generators' speed deviation and the active power output are monitored before and after the contingency. These quantities are then used by the clustering algorithm to identify the coherent clusters. Using equation (4.5), the monitored quantities are used to derive the equivalent data set represented by equation (4.6) which includes equivalent measures for rotor speed deviation for the all considered contingencies.

B. *Results and Discussions*

Once the equivalent data set of the rotor speed deviation for all generators is computed, the algorithm then computes the dissimilarity coefficients between each pair of generators as illustrated by equation (4.2). The pair with the smallest coefficients is then merged into one cluster. The dissimilarity coefficient matrix is then updated as shown by equation (4.3). The process is repeated until the final cluster is obtained as described in the flowchart, Figure 4-3. For clarity, Figure (4-5) illustrates the cluster tree obtained by the clustering algorithm. The numbers along the x-axis represent the indices of the generators. The height of the links indicates the distance between the objects (dissimilarity coefficients). The figure also shows that a number of clusters can be assigned for such a power system.

The cluster tree shown in Figure (4-5) gives a number of possible ways to partition the study system into clusters. The next task of the clustering algorithm is to determine the right number of clusters so as to obtain the coherent groups of generators in the system. To do this, the dissimilarity coefficient at each clustering step is plotted against its corresponding cluster as shown in Figure (4-6). The data corresponding to Figure (4-6) is included in table (4.1). Referring to both figures (4-5) and (4-6), and table (4.1), it can be seen that at the beginning of the clustering the algorithm merges generators G4 and G7, Figure (4-5), as the dissimilarity coefficient between them is the smallest, table (4.1).

Figure (4-6) shows that at this stage the suggested number of clusters is 15 (i.e. G4 and G7 as a cluster and the remaining 14 generators as clusters each on their own). At the second clustering stage, generators G5 and G6 are merged into another cluster as their dissimilarity coefficient is the smallest (0.0008 from table (4.1)) after the updating of the dissimilarity coefficient matrix following the merging of G4 and G7 into one cluster. There are 14 clusters at this stage and they are formed of G4 and G7 as one cluster, G5 and G6 as another cluster, and the remaining 12 generator as clusters each on their own. At the third clustering stage, both preformed clusters (G4, G7 and G5, G6) are merged into one cluster, Figure (4-5), having the smallest dissimilarity coefficient between them (0.0021 from table (4.1)). The process of merging the generators into clusters continues until all generators in the system are grouped to form one cluster.

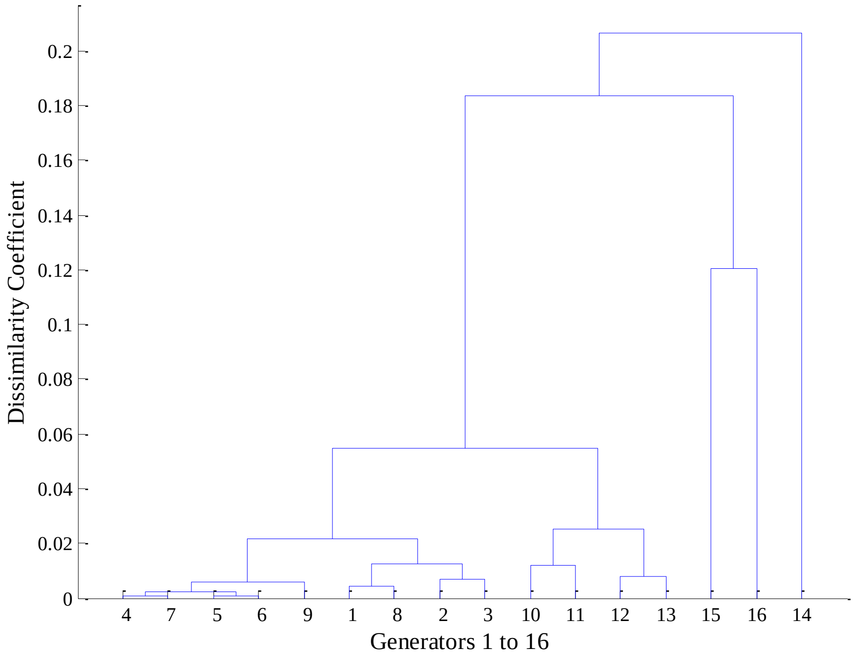

Figure 4-5: Case Study 1- The cluster tree

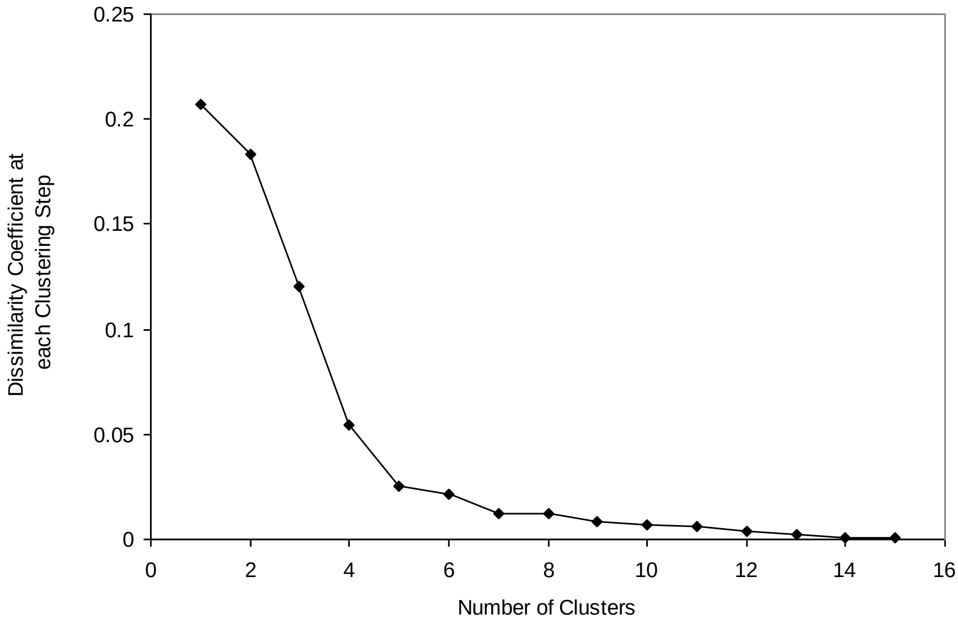

Figure 4-6: Case Study 1- The dissimilarity coefficient at each clustering step

Table 4-1: Case Study 1- Dissimilarity coefficient between clusters being merged at each clustering step

Step	Generators being merged into clusters at this step	Dissimilarity coefficient between the merged clusters	Number of clusters at this step
1	G4 and G7	0.0006	15
2	G5 and G6	0.0008	14
3	(G4,G7) and (G5,G6)	0.0021	13
4	G1 and G8	0.0042	12
5	(G4,G7,G5,G6) and G9	0.006	11
6	G2 and G3	0.0068	10
7	G12 and G13	0.0081	9
8	G10 and G11	0.0119	8
9	(G1,G8) and (G2,G3)	0.0124	7
10	(G4,G7,G5,G6,G9) and (G1,G8,G2,G3)	0.0215	6
11	(G10,G11) and (G12, G13)	0.0252	5
12	(G4,G7,G5,G6,G9 G1,G8,G2,G3) and (G10,G11,G12,G13)	0.0548	4
13	G15 and G16	0.1205	3
14	(G4,G7,G5,G6,G9 G1,G8,G2,G3 G10,G11,G12,G13) and G15,G16	0.1835	2
15	(G4,G7,G5,G6,G9 G1,G8,G2,G3 G10,G11,G12,G13 G15,G16) and G14	0.2067	1

It is clear from Figure (4-6) that as the algorithm continues merging the system's generators into groups of coherent generators, the dissimilarity coefficient at each clustering step increases gradually. As the clustering continues towards the one clustering cluster the dissimilarity coefficient increases rapidly, indicating that the clusters are becoming distinct. For example when the generators are grouped into 3 clusters, the dissimilarity coefficient between the clusters being merged at this step is 0.1205 (Figure (4-6) and table (4-1)), and it would be good practice to obtain the clusters prior to this point. This feature of the algorithm gives a very good indicator of how good the clustering is. And depending on how coherent the clustering is needed to be, one can decide where to prune the cluster tree to partition the system into the required clusters. The *"knee of a curve"* technique described in [48] is a good practice which is used to determine the number of clusters in hierarchical clustering algorithms. This technique can be applied to Figure (4-6) to determine the appropriate number of clusters for such a system. It can be seen that the *"knee"* point in the curve shown in Figure (4-6) occurs when the system's generators are grouped into 5 clusters. This suggests that 5 clusters would be a reasonable number for the system under study.

From Figure (4-5) these clusters will be formed as shown in table (4.2). The number of clusters and the formation of these clusters obtained by the proposed algorithm are exactly the same as those given by Rogers [20]. However, Rogers's technique uses coherency property derived from the angle components of eigenvectors of the inter-area oscillation modes to identify relatively closely coupled generators. Such an approach requires the computation of eigenvalues and eigenvectors for the linearised system model; hence, an enormous storage requirement for the state-space matrix that arises from the large and complex systems is needed. Also a good deal of computation time is required to find the eigenvalues and eigenvectors of such a large matrix.

Table 4-2: Case Study 1- Clusters formation

Cluster 1	G4,G7,G5,G6,G9,G1,G8,G2,G3
Cluster 2	G10,G11,G12,G13
Cluster 3	G14
Cluster 4	G15
Cluster 5	G16

The clustering configuration is also confirmed in [41] for the same test system using a different approach that is based on applying Fourier analysis to the monitored generators' speed. The advantages of the proposed method lies on the fact that it is based on simple direct measurements that can be easily obtained by a wide-area measurement system and also on the technique used to account for the effect of different possible events on the formed clusters. Therefore, it is guaranteed that the formed clusters configurations are the most likely ones to be formed under any possible operation scenarios. Figure (4-7) shows the clusters formation of the system.

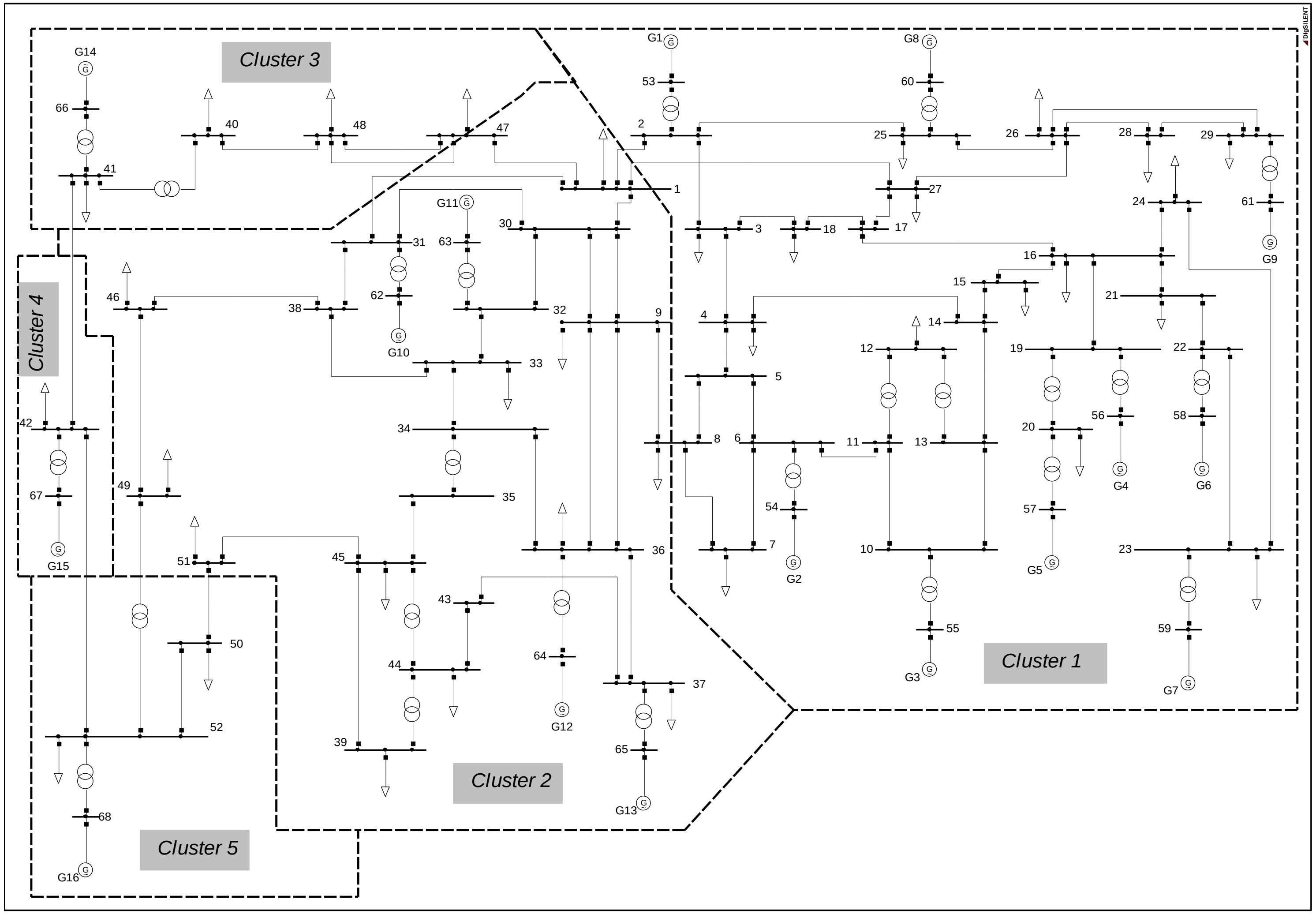

Figure 4-7: The five clusters for the 16 generator 68 bus test system

4.4.2. Verification of clusters formation

To give an insight into the clustering formation and to show how the formed clusters are coherent, the equivalent dynamic responses of the generators in all clusters are studied. As mentioned previously in the events configuration section (A), 62 credible events were simulated; those correspond to the 62 transmission line in the system. The equivalent dynamic response represented by the equivalent rotor speed deviations of all generators in the system was calculated using equation (4.4) to (4.6). This equivalent dynamic response was plotted in the time domain for a period of time equal to 20 seconds to show the coherency property between the generators relative to their formed clusters as shown in figure (4-8). As can be seen from figure (4-8), there were five distinctive groups of response profiles. The equivalent responses of generators G1 to G9 were similar and close to each other (i.e. generators in this cluster follow a similar response profile for all considered contingencies). On the other hand, generators G10, G11, G12 and G13, which form the second cluster, followed another group of response profiles. Their dynamic response was coherent between them; however it differed considerably from the equivalent dynamic profiles of other clusters. The remaining three clusters consisted of a single generator for each case, G14, G15 and G16. As can be seen their equivalent dynamic response differed from all other clusters which indicated that these generating units were not coherent with other generators within the system. The difference between these coherent groups could be identified from figure (4-8) in the following:

1- Generators G16 and G15, which correspond to cluster 4 and 5 respectively (see figure 4-7), had an anti-phase oscillatory response with regard to the remaining clusters.
2- Generator 14, which correspond to cluster 3, although it oscillated in-phase with cluster 1 and 2 it had a phase lead response profile compared to cluster 1 and cluster 2 (i.e. it had an earlier response).
3- Cluster 1 had a higher frequency of oscillations compared with cluster 2.

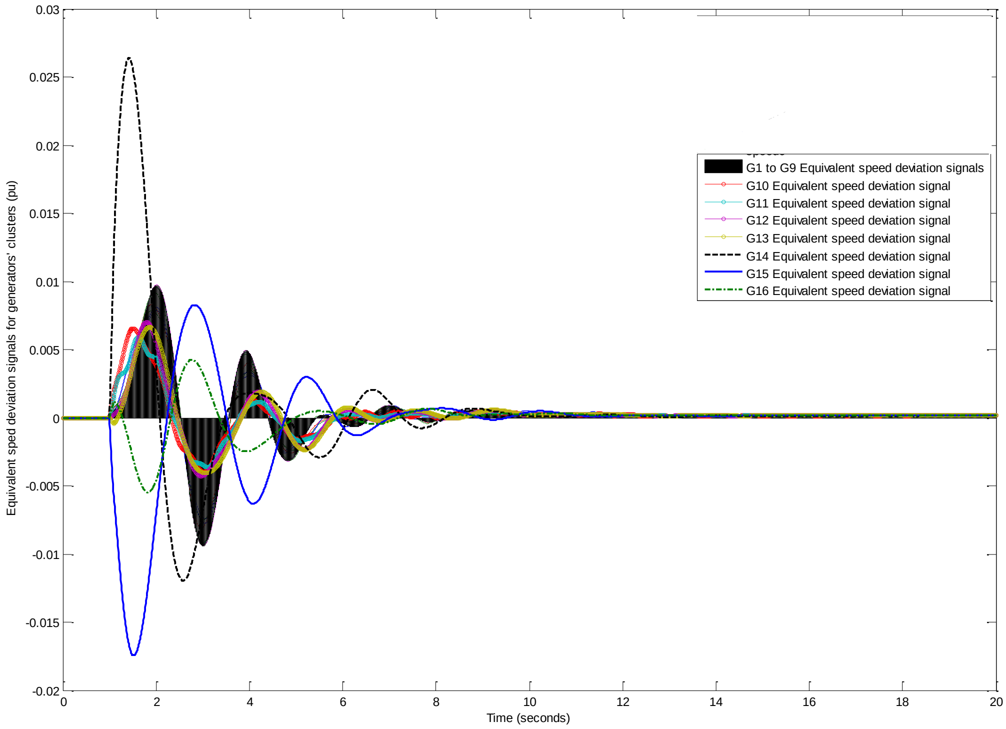

Figure 4-8: The equivalent speed deviation signals for the five clusters' system

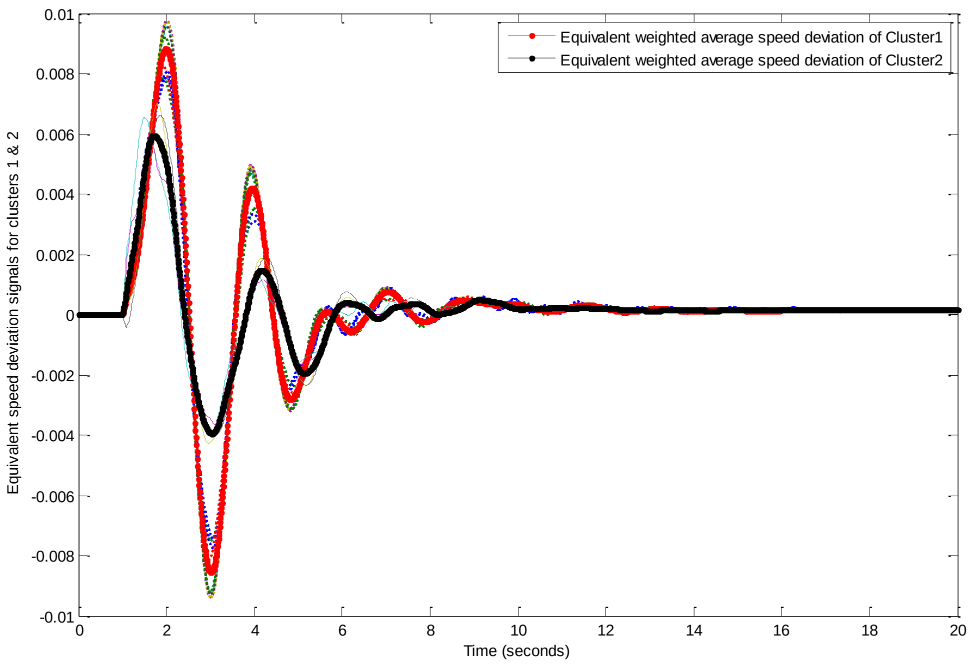

Figure 4-9: The equivalent speed deviation signals for clusters 1 & 2 along with their representative weighted response

Figure (4-9) shows the dynamic response of generators in cluster 1 and generators in cluster 2 along with the representative weighted average response for each clusters, 1 and 2. The red curve profile shows the equivalent weighted average speed signals of all the generation units in cluster 1 (i.e. generators G1 to G9), whereas the black curve profile shows that of cluster 2 (i.e. generators G10, G11, G12 and G13). These two plots confirm two groups of coherent clusters as explained with regard to figure (4-8). It can also be seen in more details that Cluster 1 is oscillating in higher frequency than that of cluster 2 with a slight phase lead to cluster 2. The time domain dynamic profiles shown in figures (4-8) and (4-9) confirm the results obtained by the clustering algorithm. It complies with the cluster formation in table (4-2). This verifies and supports the developed clustering algorithm and encourages using it in other systems to identify the coherent clusters.

4.4.3. Case Study 2: IEEE 10 generators 39 bus system

The algorithm is also applied to standard IEEE 10 generators 39-bus system. This study system is widely used for power system stability studies. It consists of 39 buses with generation units interconnected via high voltage transmission lines and supplying 19 load points. The system is modelled in DIgSILENT in details. All units are equipped with excitation systems and governors control. The system detailed data can be found in [49] and in [30] and also is included in Appendix A2. The system single line diagram is shown in Figure (4-10).

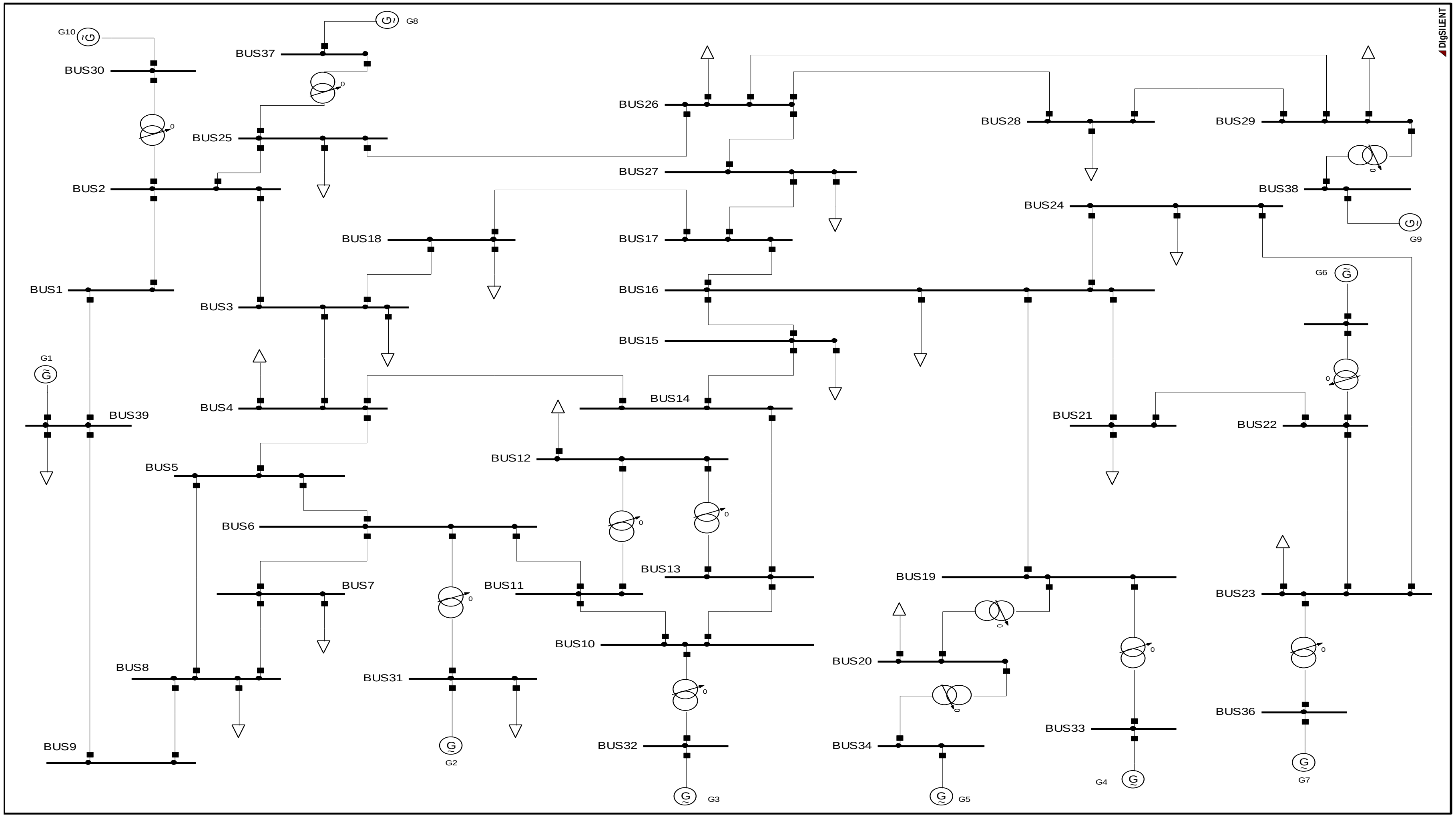

Figure 4-10: IEEE 10 machines 39 bus system

A. *Events Configurations*

Similar to the previous case study, all possible line outages are considered, hence, all generation units are included in the clustering. There are 34 transmission lines which implies possible of 34 line outage. For each line, a three phase fault is applied at 50% of the line length followed by a permanent disconnection of the faulted line. The fault occurs at 1 sec and is cleared within 50 msec by tripping the line. For each contingency the generators' speed deviation and real power outputs are measured. These measured quantities are then used by the clustering algorithm to determine the degree of coherency between the system's generators and to identify the coherent clusters as described by the algorithm flow chart, Figure (4-3).

B. *Results and Discussion*

The clustering procedure described by the algorithm when applied to the IEEE 10 machines 39 bus system results on a cluster tree shown in Figure (4-11). As indicated in the previous case study, the numbers along the x-axis represent the indices of the generators; the height of the links indicates the distance between the objects (dissimilarity coefficients). The figure also shows that a number of clusters can be assigned for this particular power system.

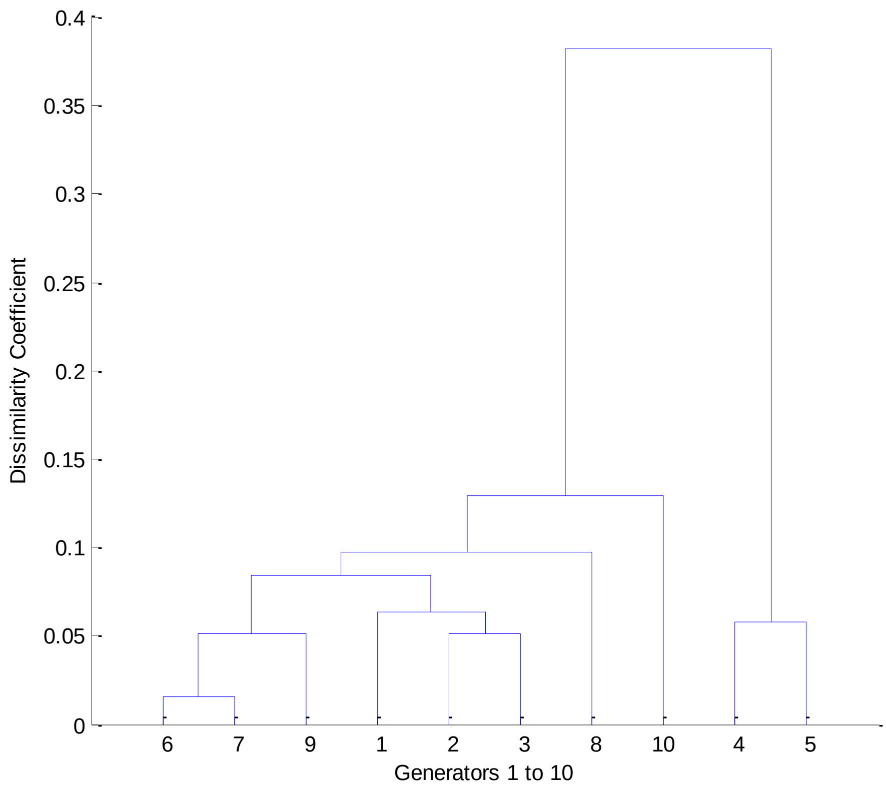

Figure 4-11: Case Study 2- The cluster tree

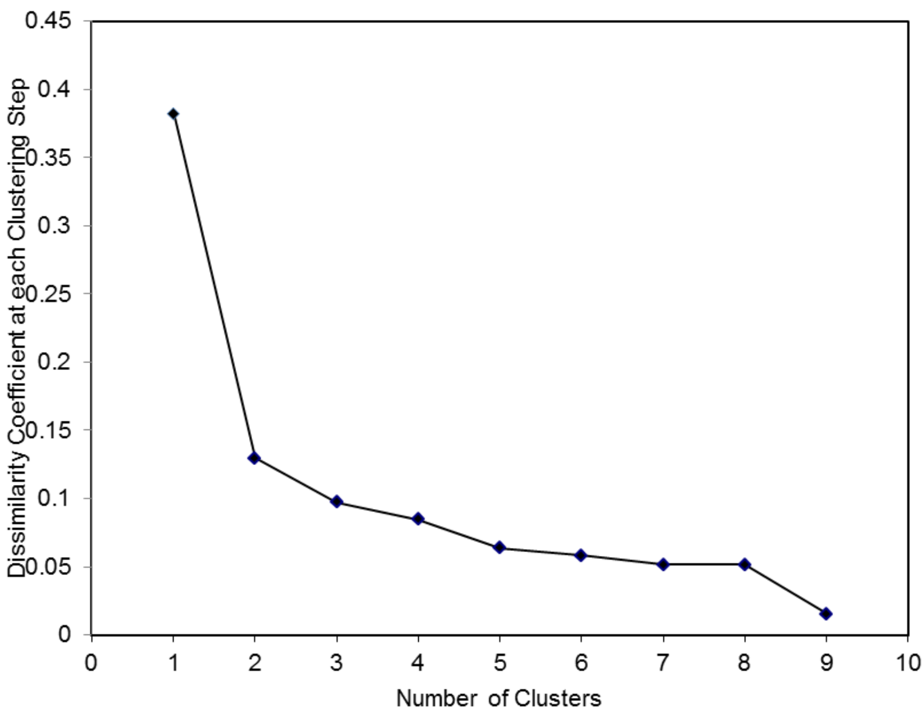

Figure 4-12: Case Study 2- The dissimilarity coefficient at each clustering step

Table (4.3) shows the formation of the clusters and the dissimilarity coefficient corresponding to the merged clusters at the indicated cluster step. Figure (4-12) shows how the dissimilarity coefficient changes as the clusters are formed. Referring to both figures (4-11) and (4-12), it can be seen that at the beginning of the clustering the algorithm merges generators G6 and G7 as the dissimilarity coefficient between them is the smallest (0.0154). At this stage the suggested number of clusters is 9 (i.e. G6 and G7 as a cluster and the remaining 8 generators as clusters each on their won). The process of merging clusters continues based on the dissimilarity coefficient between them until all system's generators are merged into one final cluster as shown in Figure (4-11) and (4-12).

Table 4-3: Case Study 2- Dissimilarity coefficient between clusters being merged at each clustering step

Step	Generators being merged into clusters at this step	Dissimilarity coefficient between the merged clusters	Number of clusters at this step
1	G6 and G7	0.0154	9
2	(G6,G7) and G9	0.0514	8
3	G2 and G3	0.0516	7
4	G4 and G5	0.0582	6
5	(G2,G3) and G1	0.0635	5
6	(G1,G2,G3) and (G6,G7,G9)	0.0846	4
7	G8 and (G1,G2,G3,G6,G7,G9)	0.0974	3
8	G10 and (G1,G2,G3,G6,G7,G8,G9)	0.1296	2
9	(G4,G5) and (G1,G2,G3,G6,G7,G8,G9,G10)	0.3821	1

It is also worth noticing that the algorithm merges generators G4 and G5 early in the clustering process having a dissimilarity coefficient of (0.0582) between them. However, their cluster is only joins the rest of the clusters at the last stage of the clustering. This shows that generators G4 and G5 form an indistinct cluster together and are distinct from the remaining group of clusters. This is due to its weak coupling to the network as it is connected to the rest of the power system by only one transmission line. This leaves this particular cluster (G4, G5) prone to inter-area oscillatory behaviour against the rest of the system. This, actually, is a good indicator of the robustness of the proposed algorithm and its effectiveness in identifying coherent clusters in a power system. From figure (4-10), the knee point of the coherency trend curve occurs when the system's generators are grouped into 2 clusters. This justify considering this particular system as a 2 coherent clusters system. From Figure (4-10) these two cluster formation will be formed as shown in table (4.4). The two clusters are shown in figure (4-13)

Table 4-4: Case Study 2- Clusters formation

Cluster 1	G1,G2,G3,G6,G7,G8,G9
Cluster 2	G4, G5

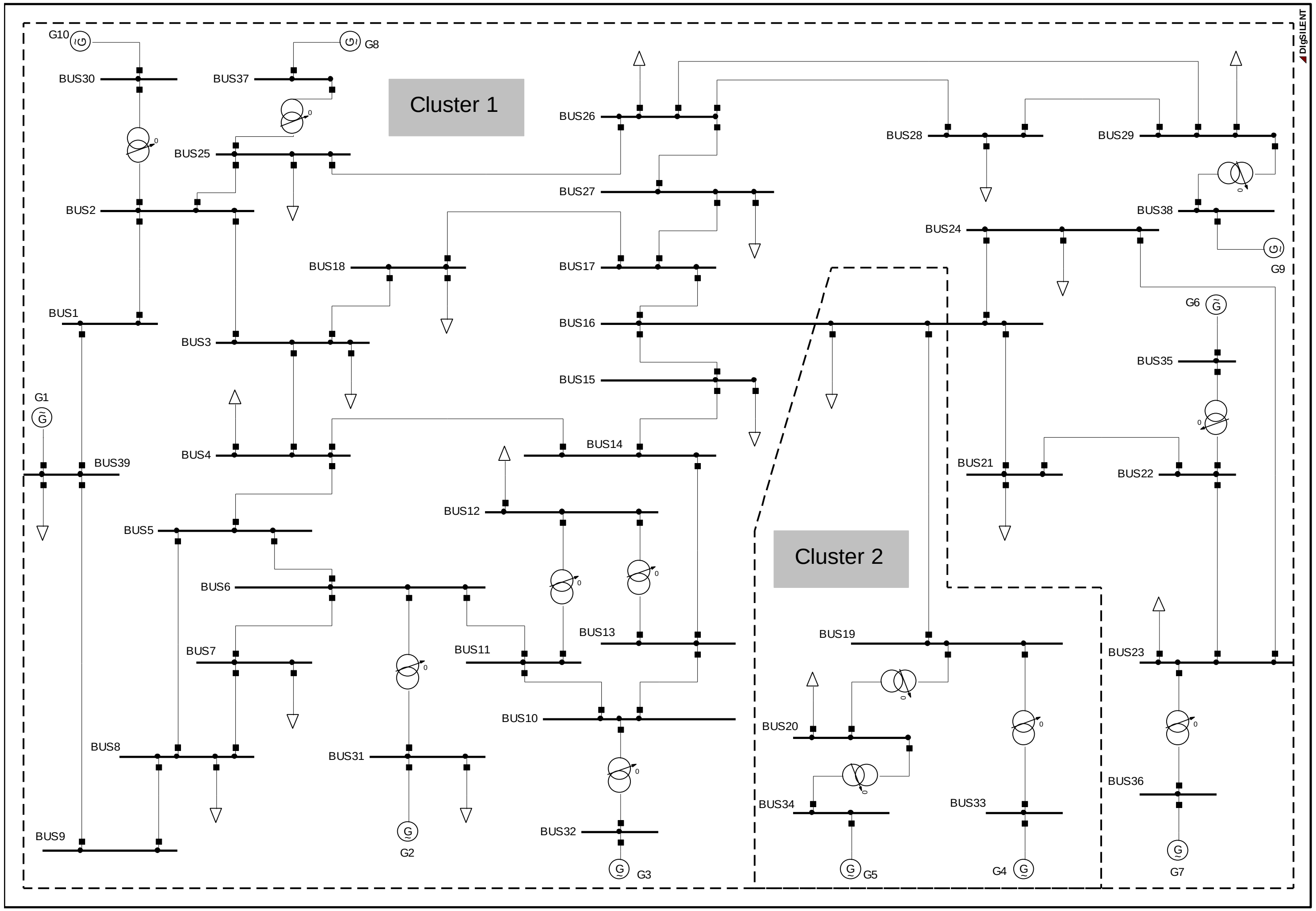

Figure 4-13: The two clusters of the IEEE 39 bus system

4.5. Summary

A new method to determine coherent clusters of synchronous generators in a multi-machine power system is presented in this chapter. The method is suitable for implementation in wide-area measurement systems as it allows the identification of coherent clusters based on wide-area signal measurements of generator rotor frequencies (speed deviation in the presented work). It comprises coherency measures extracted from generators rotor signal measurements and an agglomerative clustering algorithm to group generators into coherent clusters. The merits of this method can be summarized in the following:

- Coherency between the system's machines is extracted from direct measured quantities. This implies that if the required measurements are available, then the coherent clusters can be identified directly based on these measurements without the need for the system model.
- A new technique that uses generators active power output measurements to account for the effect of different types of events on the clusters configurations is introduced in the proposed method. Thus, the accuracy in the clustering is assured.

The algorithm is tested on two standard multi-machines test systems, the standard 16 generator 68-bus system and the IEEE 10 machines 39-bus system. The obtained results are presented and discussed. The results show the effectiveness of the proposed algorithm in fast identification of coherent clusters in a multi-machine power system. Having identified coherent clusters in a given power system, it becomes possible to develop techniques to identify which cluster is more critical for the system stability. It also becomes possible to identify critical tie-lines (those lines that connect the clusters to each other) only by visual inspection to the network topology. Such critical lines, where system oscillations are highly observable, can be monitored and wide-area measurement devices can be located. Remote signals from these critical tie-lines can be acquired using WAMS synchronised measurements and then used as wide-area remote feedback signals to local damping devices such as the conventional local power system stabilisers (CPSSs) to improve their effectiveness in damping inter-area system oscillations.

Identification of key clusters for potential control enhancement and development of wide-area based control schemes are the focus of the following chapters where those research aspects is investigated in details.

Chapter 5: Identification of Key Clusters for Potential WAM based Control

5.1. Overview

WAMS applications in power systems suggest that a potential enhancement to the dynamic performance of large interconnected multi-machine power systems can be accomplished [8], [12], [18], [13]. Wide-area based stability controllers have been, recently, the subject of a considerable research. To achieve best system performance, however, wide-area based controllers have to be located at optimally identified critical areas from which system instability phenomenon may originate. The identification of critical areas within a power system for potential wide-area based control development contributes significantly to achieving enhanced system performance under increasingly stressed operation conditions.

Instabilities phenomenon that may limit better system utilization are caused mostly by electromechanical oscillations between separated areas connected through long distances transmission networks [19], [21]. The frequency of these oscillations and the number of synchronous machines involved in any electromechanical oscillatory mode depend on the structure of the power system network. In General, low frequency electromechanical oscillations are more likely to be observed when geographically dispersed generation/load areas are connected to each other via relatively weak transmission lines compare to the rest of the transmission network [20]. The weak interconnections can be obvious when, for example, two independent power system networks are interconnected through a single tie-line. However, for systems which have been interconnected for a period of time, electromechanical oscillations may appear due to stressed operation conditions and increases in power transfer across the transmission network. In such cases, identifying critical transmission lines and critical areas from which oscillatory system behaviour may originate becomes a vital task for stability studies and control of power systems. Experiences and observations of the operation of power systems networks show that disturbances or changes in the operation conditions of a stressed power system may give rise to electromechanical oscillations between interconnected synchronous generators. In such circumstances power systems tend to oscillate coherently with groups of generators in a specific area of the power system behaving coherently in low frequency electromechanical oscillations. Those groups of coherent generators are separate, yet connected, to other groups of coherent generators by weak transmission lines. Identification of theses coherent groups of machines is important, from the control and operation point of view, for the design of stability control schemes that aim to arrest system instabilities. In chapter 4 a novel technique to identify those coherent clusters or groups of synchronous generators is described and tested. In this chapter (chapter 5), the technique is updated such that critical key areas for essential wide-area based control can be determined, critical tie-lines can be observed, and; hence, control measures for those areas can be assigned.

5.2. Concept and Implementation

In chapter 4, the coherency properties between power system synchronous generators is determined by simply evaluating the Euclidean Distance, which is referred to as the dissimilarity coefficient, between any two arbitrary generating units in the system. The obtained coherency properties is used identify all the coherent clusters within a power system as demonstrated in case studies in chapter 4 and in [50]. Once those coherent clusters are identified, the concept of Centre of Inertia introduced in [46] can be used such that each coherent cluster is presented by its approximate centre of angle (inertia) as shown by equation (5.1).

$$\delta_{COI}^{i} = \frac{\sum_{j=1}^{N^i} \delta_j^i P_j^i}{\sum_{j=1}^{N^i} P_j^i} \qquad (5.1)$$

Where:

δ_{COI}^{i} is the centre of inertia of cluster *i*.

δ_j^i is the rotor angle measurements of the j^{th} generator in cluster *i*.

P_j^i is the active power generation of the j^{th} generator in cluster *i*.

N^i is the number of generators in cluster *i*.

The centre of inertia for the entire system can similarly be computed as in equation (5.2).

$$\delta_{COI} = \frac{\sum_{i=1}^{N} \delta_{COI}^{i} P^{i}}{\sum_{i=1}^{N} P^{i}} \qquad (5.2)$$

Where

δ_{COI} is the centre of inertia of the entire system.

P^i is the total active power generation in cluster *i*.

N is the total number of clusters.

If the representative angle (inertia) δ_{COI}^{i} of a cluster (*i*) is continuously increasing away from the centre of inertia δ_{COI} of the entire system, then this will be understood as if area (*i*) is moving towards instability and, therefore, is most critical.

5.3. Case Study

The standard 16-generator 68-bus system is used as a case study to implement the proposed technique described above. Such a system is ideal to test the algorithm as it includes five distinctive clusters and a number of tie-lines connecting those clusters for which a number of scenarios can be considered. The system is used in previous chapter to test the clustering algorithm which have resulted in five clustering formation similar to those described in [20]. Subsequently, all system clusters will be represented by their representative equivalent angle using equation (5.1), all of which will be evaluated with regard to the equivalent centre of inertia of the entire system.

A. *Simulation Scenarios*

To illustrate the functionality of the proposed technique in representing each coherent cluster by its representative angle based on the concept of Centre of Inertia COI as shown by equations (5.1) and (5.2), a number of simulation scenarios are considered.

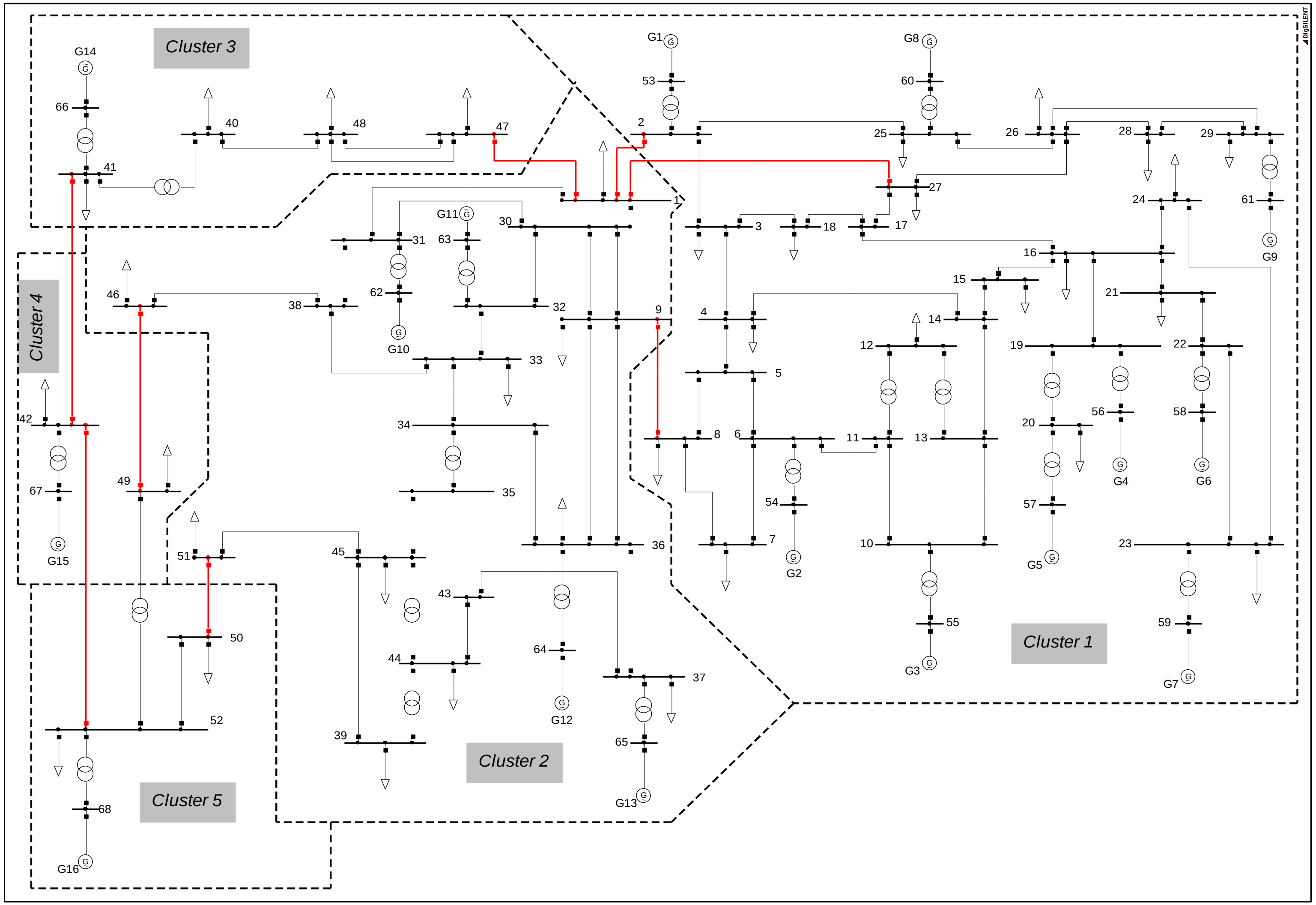

Figure 5-1: The five clusters of the 16 generator 68 bus test system with critical tie-lines

From the network topology, following the identification of the coherent clusters, a number of lines are identified as being critical to the system stability due to their unique configuration within the system (i.e. being the lines connecting the coherent cluster). By visual inspection of Figure (5-1), eight lines can be of interest; those lines are as shown in table (5.1). Two different scenarios are considered for each of the lines included in table (5.1). The first scenario is applying a three phase fault at 50% of the lines length which leads to a permanent disconnection of the faulted line. The other includes applying a transient faults on the lines which are cleared by disconnecting both ends of the faulted line for a period of time and then reclosing the line; this is similar to the function of auto reclosing schemes. All faults occur at 1.0 sec; faults duration is set to 16 cycles (0.32 sec) after which the faulted line is either disconnected permanently to clear the fault or is disconnected for a period of time equal to 5 cycles (0.1 sec) and then reclosed, in the case of transient faults.

Table 5-1: Critical lines considered in simulation

Tie-lines	Description
1-2, 1-27, and 1-47	Connecting clusters 1, 2, and 3
8-9	Connecting clusters 1 and 2
41-42	Connecting clusters 3 and 4
46-49 and 50-51	Connecting clusters 2 and 5
42-52	Connecting clusters 4 and 5

B. *Results and Discussion*

Figures (5-2), (5-3) and (5-4) show results with regard to the first set of lines in table (5.1), the lines connecting clusters 1, 2 and 3. The (a) figures show the results when these lines are brought back into service following the clearance of the fault whereas the (b) figures shows the results when the same lines are permanently disconnected from the network. Figure (5-2 (a) and (b)) shows that fault on line 1-2 have a similar effect on all clusters in both cases (permanent and transient fault). Cluster 1 seems to encounter most of the impact as its first swing is the highest and is in an anti-phase to the rest of the system's clusters. This gives an indication that cluster 1 is oscillating against the rest of the system for this specific event. It is also clear that disconnecting line 1-2 permanently, figure (5-2 (b)), does not affect the system significantly apart from higher first swings especially in cluster 1. On the other hand, the system seems to behave differently at the presence of faults on line 1-47, figure (5-3 (a) and (b)). For the first scenario (i.e. when the line is brought back into service following fault clearance), figure (5-3 (a)), the impact on the clusters is not significant. However, if the line is to be disconnected permanently, a significant increase on the representative angles of both clusters 3 and 4 are observed. Also clusters 1 and 2 seem to be effected by disconnecting the line as their representative angle decreases. The impact on cluster 5 is less significant.

The concept of the clusters' representative angles gives important information on how each cluster of synchronous generators behave when changes occur in the system. This allows effective measures to be taken to improve the system's stability. In the previous described case, for example, clusters 3 and 4 are important candidates to implement stability enhancement measures. Line 1-47 is also an important part of the system which should be taken into account for further improvement of the system performance. Figure (5-4 (a) and (b)) show the response of the system's clusters to faults on line 1-27. The impact of both scenarios on this line is similar to the previously described for line 1-2 with cluster 1 oscillating against the rest of the clusters. This conclude that, as far as the first set of lines included in table (5.1) is concerned, line 1-47 seems to be the most critical for the system stability and cluster 3 is most critical in the case of permanent disconnection of this line. Cluster 1 appears to oscillate against the rest of the system in the presence of any of the discussed scenarios.

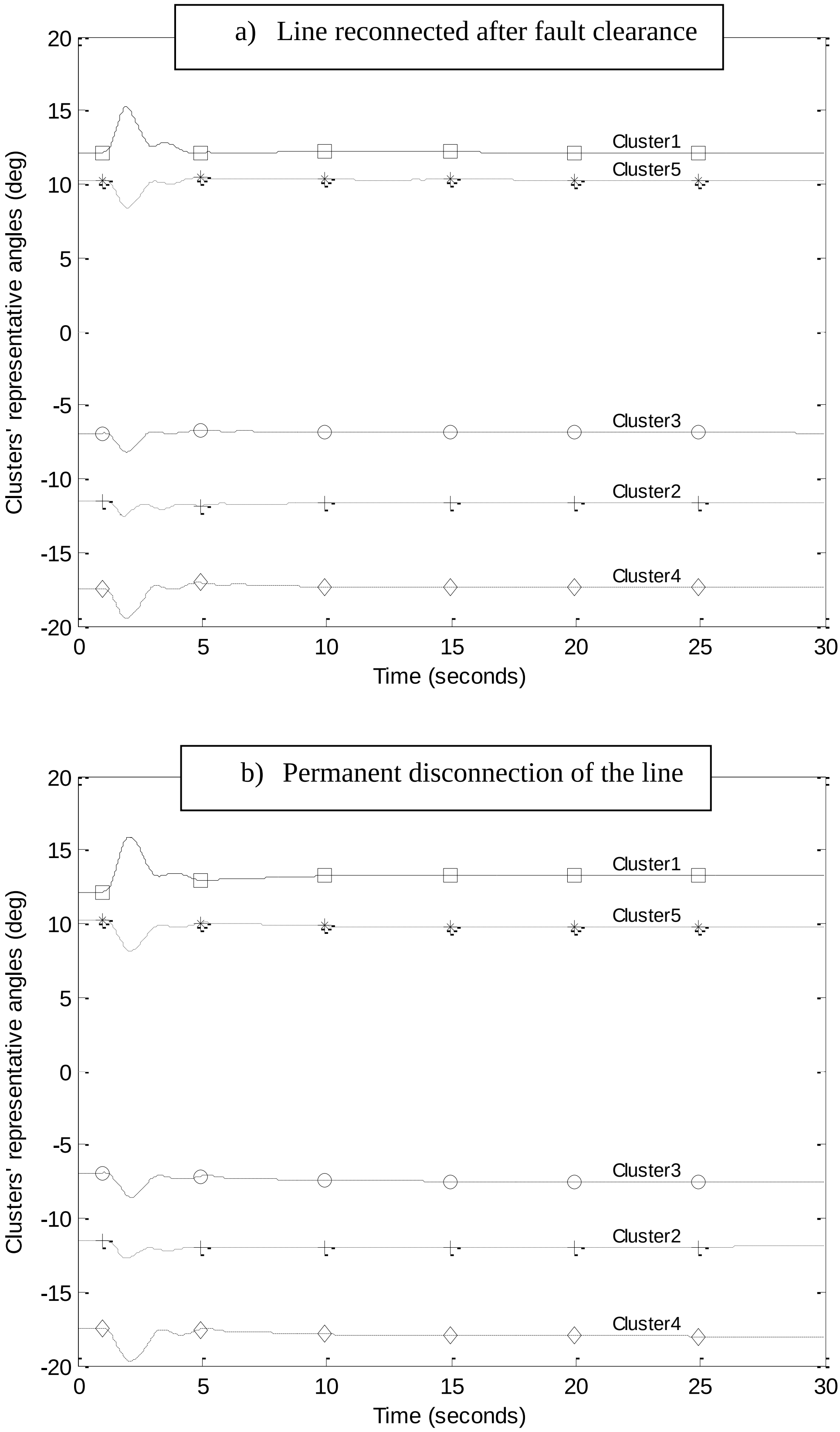

Figure 5-2: Fault on line 1-2/ 16 machine test system

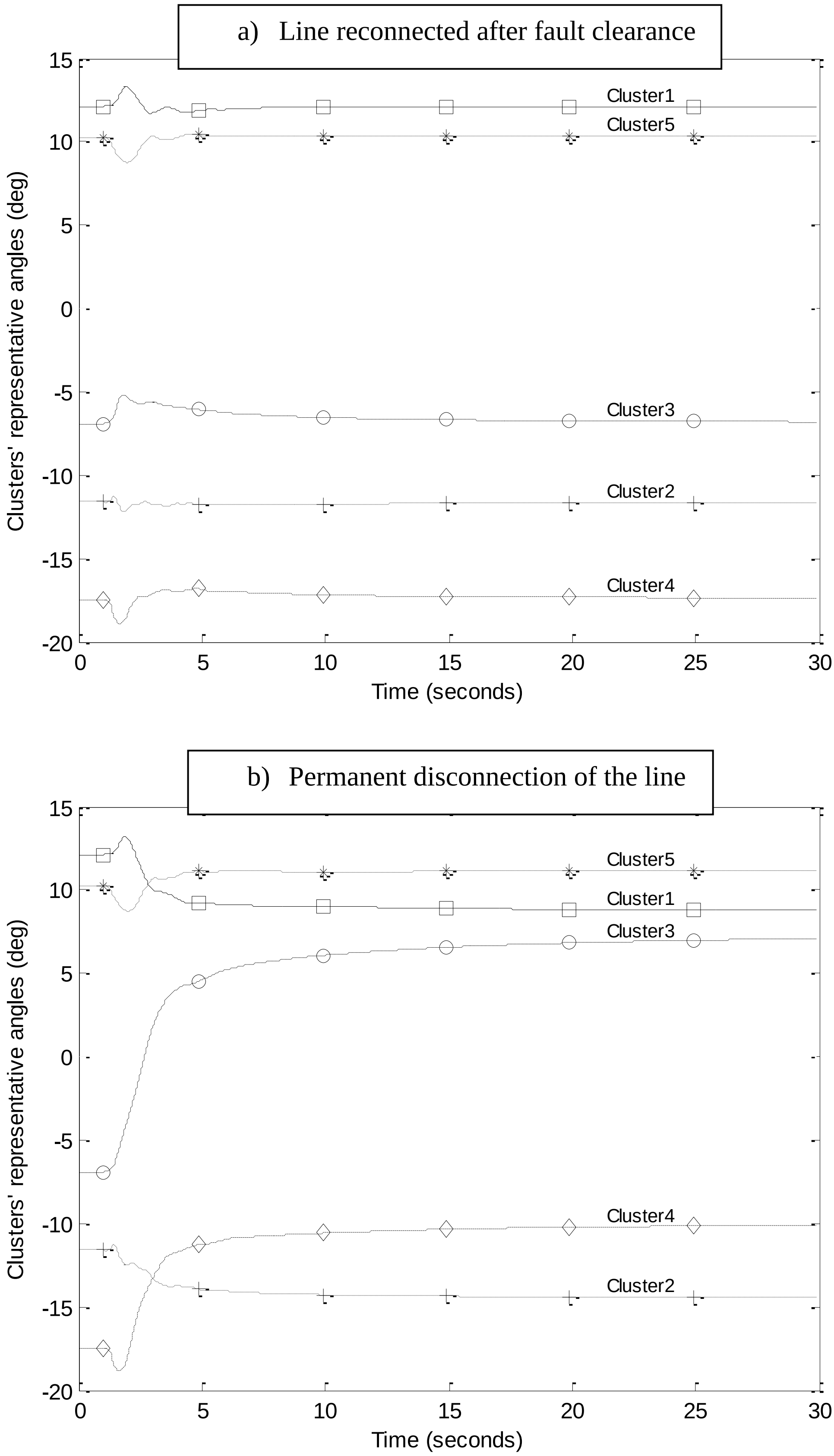

Figure 5-3: Fault on line 1-47/ 16 machine test system

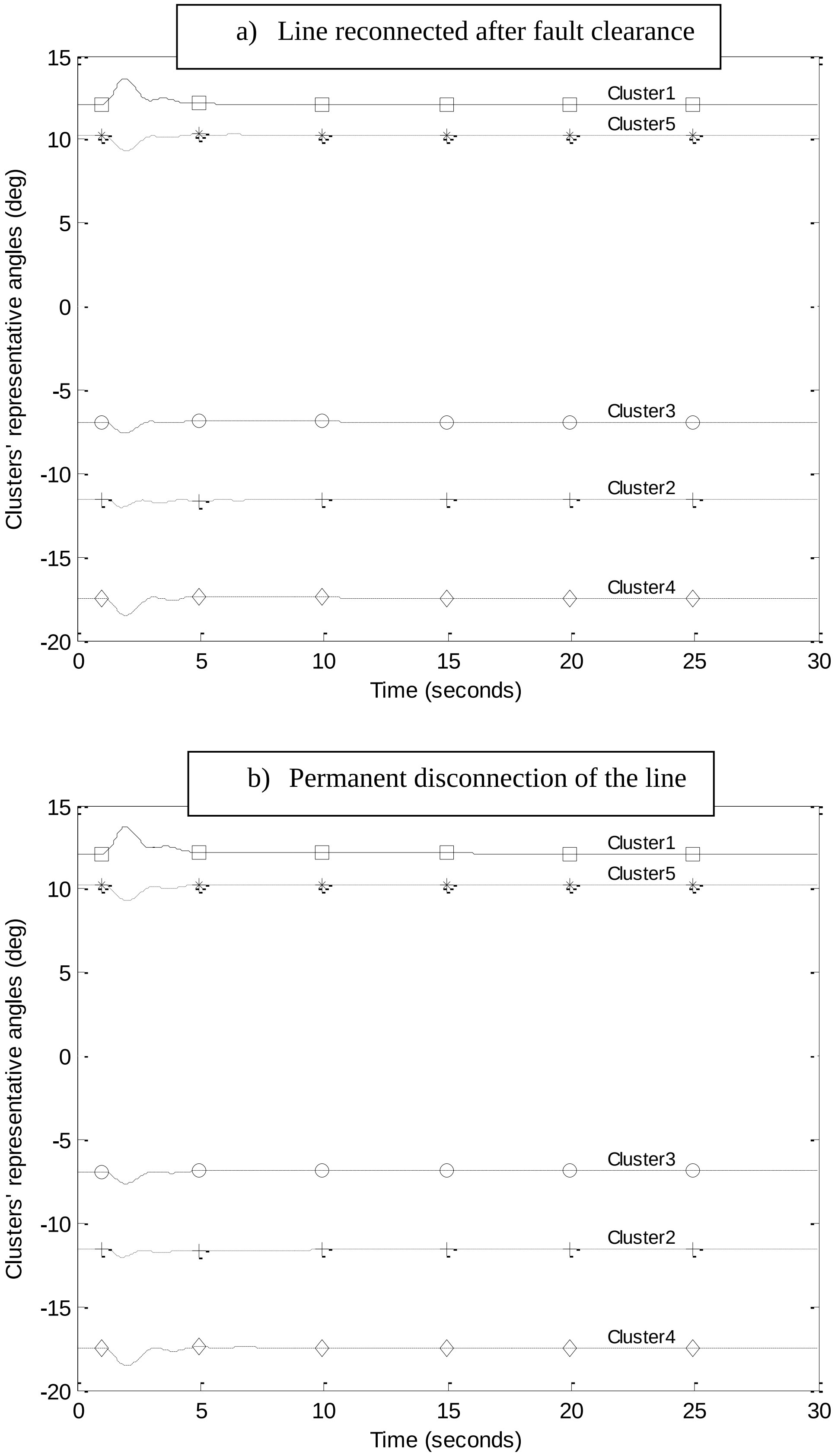

Figure 5-4: Fault on line 1-27/ 16 machine test system

Simulation results for the line 8-9 connecting cluster 1 and 2 are shown in figure (5-5 (a) and (b)). Again, cluster 1 seems to oscillate against the remaining groups with a higher swing in its representative angle when the line is permanently disconnected.

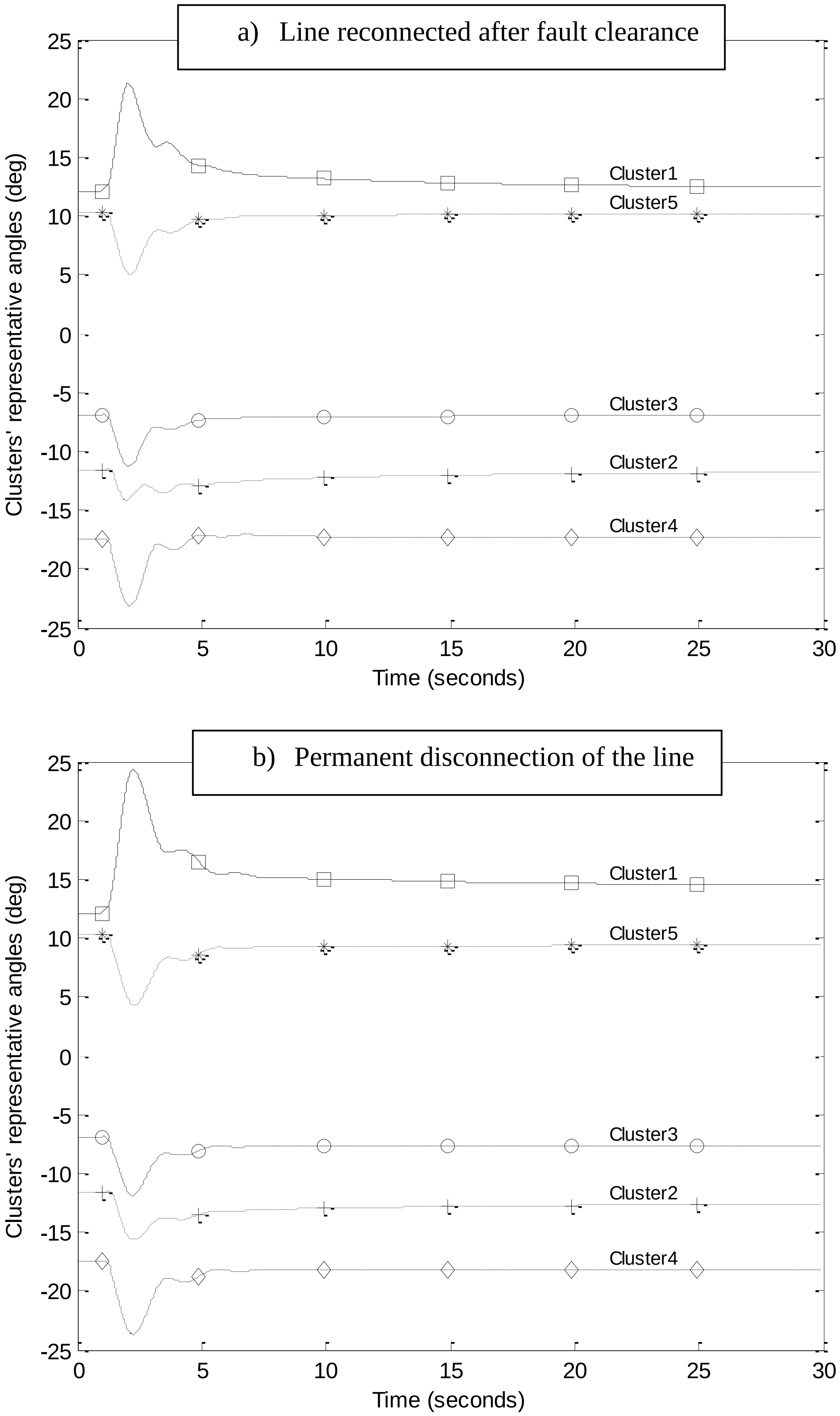

Figure 5-5: Fault on line 8-9/ 16 machine test system

Figures (5-6) and (5-7) show results for the set of lines connecting the coherent clusters 2 and 5 (line 46-49 and line 50-51 respectively).

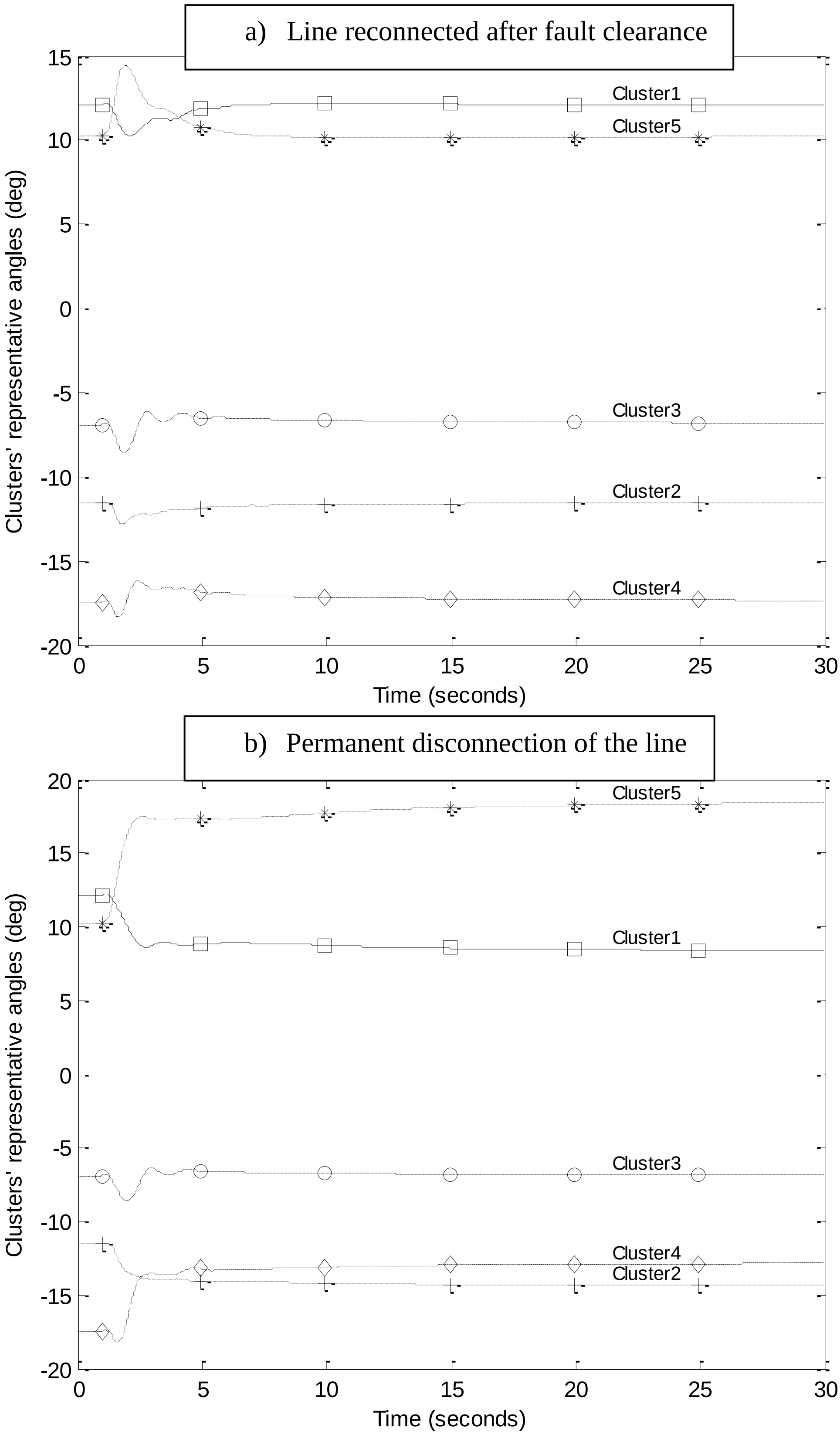

Figure 5-6: Fault on line 46-49/ 16 machine test system

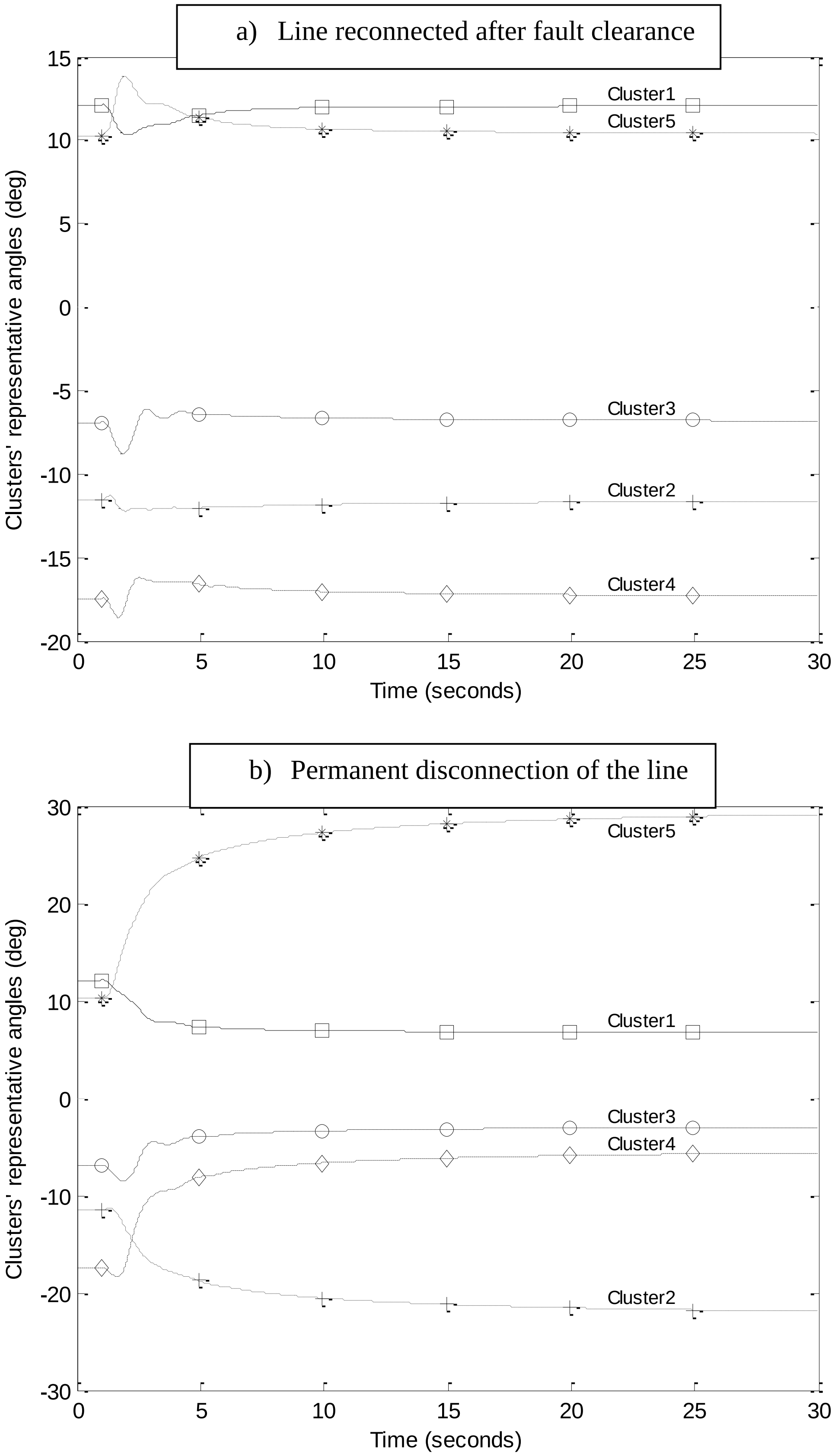

Figure 5-7: Fault on line 50-51/ 16 machine test system

Figure (5-6 (b)) however shows a different scenario as line 46-49 is permanently disconnected to clear the fault. Clearly, cluster 5 encounters most of the impact as its representative angle increases significantly. Figure (5-7 (b)) also shows that permanent disconnection of the other line connecting cluster 2 and 5 (line 50-51) causes the representative angle of cluster 5 to increase significantly away from the rest of the system. It also shows that cluster 2 in the other end of the critical line under consideration seems to oscillate against cluster 5 (keep in mind that these two clusters are connected by the line under consideration).

Figure (5-8) and show the results with regard to line 41-42 connecting clusters 3 and 4 whereas figure (5-9) shows the results for line 42-52 connecting clusters 4 and 5.

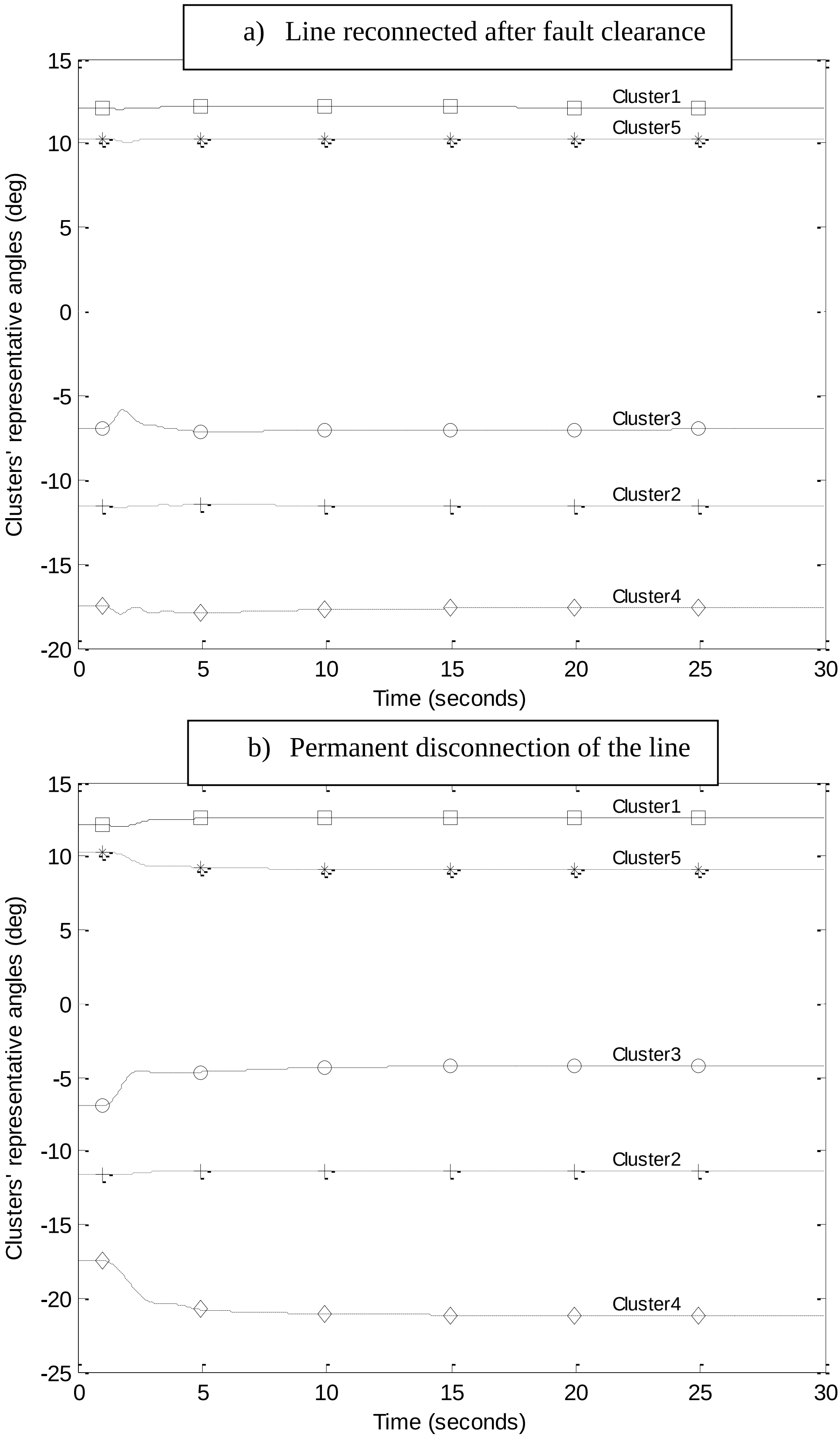

Figure 5-8: Fault on line 41-42/ 16 machine test system

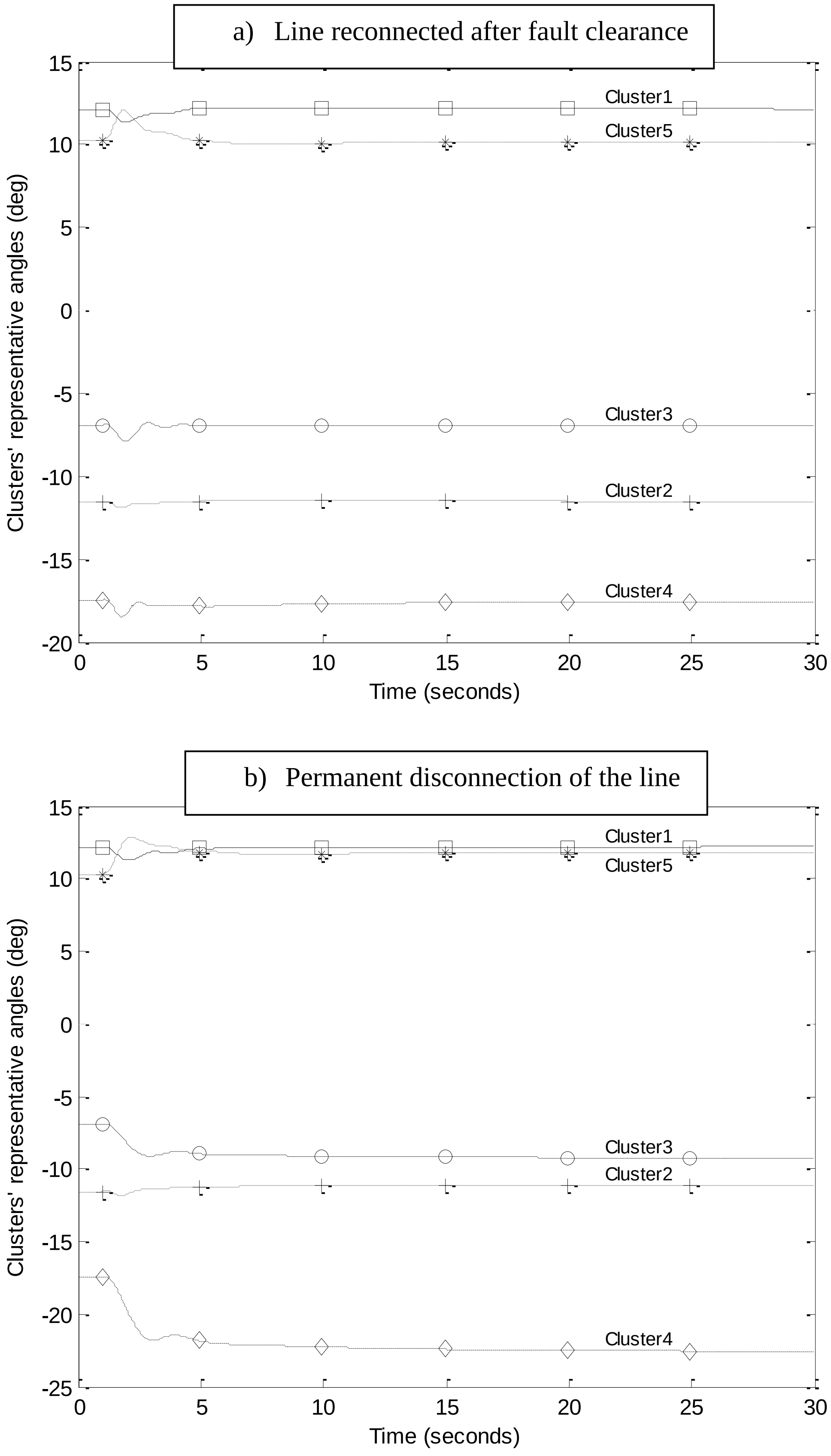

Figure 5-9: Fault on line 42-52/ 16 machine test system

5.4. Summary

A method to evaluate critical areas and critical lines in multi-machine power systems is discussed in this chapter. The method combines the concept of Centre of Inertia COI and coherency property between synchronous generators to, firstly, identify coherent clusters of synchronous generators within the power system and, secondly, to represent each coherent cluster by its representative centre of angle (inertia). This allow for each cluster to be evaluated with regard to the centre of angle of the entire system. Hence, determine which clusters/lines are most critical for the system stability. The method is tested on the standard 16-generator 68-bus system. The reason of choosing this particular system is that is include 5 distinctive clusters and a number of tie-lines connecting those clusters for which a number of scenario can be considered. The obtained results are presented and discussed. The results show the effectiveness of the proposed technique in giving a clearer sight regarding the system stability in terms of its capability to illustrate the degree of criticality of certain areas and tie-lines connecting these critical areas. The advantages of the proposed method can be summarised in the following:

- The method is based on coherent clusters identified based on coherency property extracted from direct measurements[2]. Therefore, implementing the technique in a wide-area measurement system is applicable; hence, critical areas/lines can be identified directly without the need for the system model.

- Identifying critical areas/lines allows better control schemes based on the evolving technologies of wide-area measurement to be designed more effectively. The critical lines, for example, where the system oscillations are highly observable, can be taken as basis to provide wide-area feedback control signals for local controller and power system stabilizers to enhance their performance in damping system oscillations.

[2] As described in chapter 4

Chapter 6: Development of a Novel WAM based Control Scheme for Stability Enhancement

6.1. Overview

A reliable, continuous supply of electricity is essential for today's societies. Giving the combination of increasing energy consumption and variety of reasons that limit the extension of existing transmission networks, the situation requires less conservative power system operation style. This can be possible only by monitoring and controlling the system in a much more detailed and efficient way. In chapter 3, three different control strategies are explored. The strategies are categorised in terms of the way information are collected from the system and how control actions are taken and deployed (i.e. centralised control, decentralised control, and multi-agent control techniques). Another way of categorising control strategies is by looking at the level in which control actions are taken. In electrical power systems, a three different control levels can be identified [51]. Those control levels are:

- *Generating unit controls*: This control level consists of system components that apply their control actions directly to the generating unit. It consists of prime mover control and excitation control with automatic voltage regulators (*AVR*) and power system stabilisers (*PSS*). Prime movers control the generator speed deviation and energy supply system variables. On the other hand, excitation systems maintain the generator terminal voltage and reactive power flow within acceptable limits.

- *System generation control*: This control level aim is to determine active power output such that the overall generation is equal to the system demand. It also maintains the system frequency and controls the power flow across tie-lines between different areas within the power system.

- *Transmission control*: This control level consists of system components that monitor and control voltage levels and power flows across the transmission system such as tap-changing transformers, synchronous condensers and static *VAR* compensators.

In real system operation, these control levels are interlocked. All control actions affect both components and system. *AVRs* for example are known to introduce oscillatory modes, both local and inter-area, which are counteracted by deploying power system stabilizers *PSS*. Generating unit control is a complete closed-loop system. A considerable effort has been delegated to improve the performance of the controllers. Some of these attempts are reviewed in chapter 3. The main problem, however, is that the control law is derived based on a linearized system model in which the control parameters are tuned to some nominal operating conditions. In the case of large disturbances or power oscillations, the system state changes in a highly non-linear manner and, in some cases, controllers become ineffective. In addition, generating unit control level is considered as decentralised form of control strategies which consists mainly of local controllers that lack the ability to have a wide view of the entire system. Thus, their control actions are taken based on locally available control signals, which limit their capabilities to influence and enhance the stability of the entire system.

This chapter is focused on the phenomenon of power system oscillation and the development of a new control scheme to improve stabilisation capabilities of generating units' control. This will be carried out by means of adaptive control techniques and exploiting the advantages of wide-area measurement systems *WAMS*.

6.2. Excitation Control and Stabilisation (advantages and limitations)

In power systems, the main components used to produce electrical energy are the synchronous generators. The generator is normally driven by a prime mover and its production windings are connected to the transmission network through a step-up power transformer. Auxiliary circuits are used to control and manage the generator when connected to the grid. Figure (6-1) shows a typical complete generating unit with most auxiliary components [52]. The excitation system supplies the *DC* rotor windings with a field current (I_f) which, in turns, produces a rotating magnetic field that induces an electromotive force (*emf*) in the generator stator windings. The excitation voltage (E_f) is applied to the rotor windings and is controlled by an automatic voltage regulator (*AVR*). During normal steady-state operation, the *AVR* is very effective in keeping satisfied operation conditions. However, following a system disturbance, the system state changes significantly in a non-linear manner and the *AVR* may have a negative impact on the damping of power oscillations.

In presence of power swings, electric currents, which are proportional to the speed deviation ($\Delta\omega$) around the synchronous speed, are induced in the damper windings of the synchronous generator. These currents result in a natural damping of the rotor oscillations.

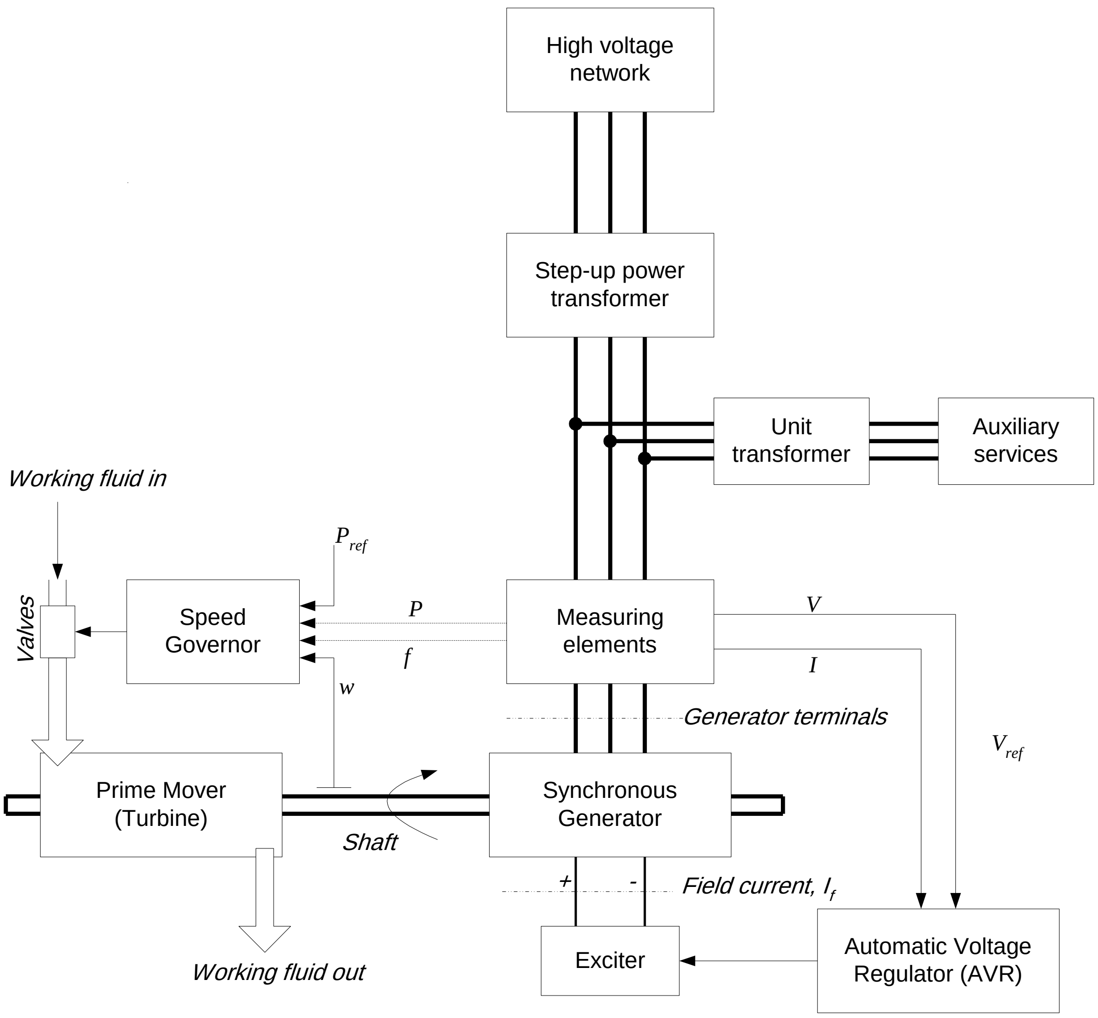

Figure 6-1: Typical generating unit with most auxiliary components [52]

As power swings cause the generator terminal voltage to oscillate, the reaction of the *AVR* forces field current changes to maintain the voltage. Under certain conditions, these field current changes may oppose the natural damping currents induced by the rotor speed deviations $\Delta\omega$. In such cases, the *AVR* actions result in an artificial damping that is large, negative and may be stronger than the natural damping. This phenomenon is known as negative damping. Negative damping causes oscillatory unstable behaviour in the system which needs to be stabilised. Power oscillations are unacceptable state of operation that needs to be dealt with effectively and any power swings have to be quickly damped. Thus, techniques to improve the performance of excitation systems in such a way that they do not introduce negative damping or, even better, that they introduce positive damping are important for more efficient, secure and reliable system operation.

One way of improving excitation systems performance is using power system stabilisers *PSSs*. The use of *PSS* is the most cost-effective and widespread method of enhancing the damping of power oscillations. The function of a *PSS* is to reduce the negative damping caused by *AVRs* actions by introducing a supplementary additional control signal that compensate for voltage oscillations and provides a damping component that is in phase with the speed deviation. Nonetheless, there are problems associated with designing a robust and an effective *PSS* which results on it being unable to provide satisfactory performance that can cope with the recent challenges facing modern today's power systems. Those problems or limitations are summarised as follows:

- A typical *PSS* produces its control actions based on a defined transfer function with constant parameters. In most cases, this transfer function consists of a washout blocks and one or more phase compensation blocks as shown in figure (6-2), [53]. Washout blocks are high-pass filters used to allow signals associated with the speed deviations to pass unchanged and to reduce the response of the damping during sever events. Phase compensation blocks are used to provide the required lead/lag characteristic to compensate for the phase shift caused by the exciter action, hence, overcome the negative damping caused by those actions. Having constant parameters means that during rabid changes in system conditions, the *PSS* control action may not be able to provide appropriate control signals which may cause system instability.

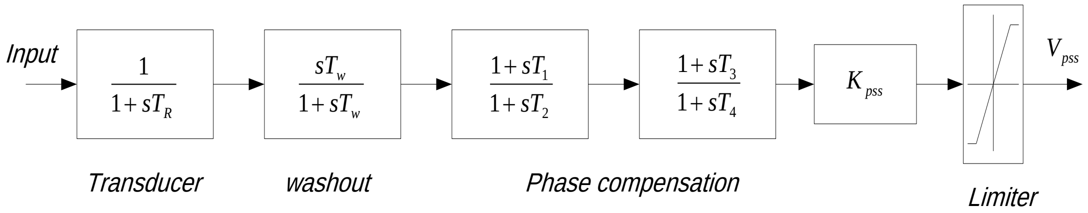

Figure 6-2: Block diagram of conventional PSS [53]

- Most conventional *PSSs* are designed using linearized system models. Using approximate linearized model of the generator and the power system, the *PSSs* are designed using linear control theory. Although this design approach may be effective during certain operation conditions, linearly designed *PSSs* may not be able to maintain adequate stable operation conditions when power systems are subjected to large disturbances that cause considerable and rabid changes in system conditions.

- Conventional *PSSs* use phase compensation blocks shown in figure (6-2) to provide an electrical torque, which is in phase with speed deviation, to compensate for the negative damping caused by actions of *AVRs*. The problem with this design approach is that these blocks usually provide efficient compensation only for a certain range of oscillation frequencies. As explained in chapter 3, the frequency range of oscillations varies considerably between local oscillation modes and inter-area oscillation modes. Therefore, it becomes very difficult to design a *PSS* that is properly tuned to be as effective for damping inter-area oscillations as it is in the case for local oscillations damping.

- Another important aspect of conventional *PSSs* is that they are decentralised local controllers that act upon locally measured feedback control signals. PSSs control based on local measurements are not always effective due to lack of global observability, mutual coordination with other individual controllers, and placement flexibility. Lack of global view of power system and absence of coordination between decentralised stabilisers may result in potentially harmful interactions between these controllers.

Obviously, to meet today's power systems operation requirements, development of control schemes to enhance the performance of existing conventional controllers is essential. Using global signals fetched from different parts of the network and applying these signals as inputs to newly developed controllers can overcome the issue of observability and lack of information of local controllers. Hence, enhance their damping capabilities to instability phenomenon cause by power oscillations. With the advent of new technologies of *PMU/WAM* based systems, it becomes possible to transmit wide-area synchronised dynamic information across the entire system and make this information available for local decentralised controllers. Also, using different control design approaches alternative to linear control design theory can help overcome the limitations inherited in such linearly designed controllers. Adaptive and artificial intelligent control design approach to develop stability enhancement schemes provide a promising way of making power systems more flexible, more adaptable to changes in the system, and overall, more capable of providing a reliable and secure source of electrical energy supply. The following sections of this thesis are focused on adaptive non-linear control approach and its application in the power system; this is *Fuzzy Logic Control (FLC)* design techniques and its application in power system.

6.3. Fuzzy Logic and its Application to Power Systems

Fuzzy logic theory has achieved considerable success in a variety of engineering practices ranging from simple small applications to sophisticated decision making and control problems. In [54], a relatively recent survey lists nearly 300 archival publications related to fuzzy logic theory and its applications in power systems. It provides a comprehensive set of references classified according to the power system area, mainly published in archival journals on the fuzzy set theory applications in power systems in the period from 1994 to 2001. In the area of power system operation and control, traditional analytical solution techniques exist to deal with power system problems. Although a considerable number of assumptions and approximations are made to achieve these mathematical formulations, the solution for a large-scale interconnected modern power system problem is not always simple and adequate to deal with ever changing system conditions. In addition, electrical power systems are large, complex extended electro-mechanical dynamic systems that are geographically widely spread and are influenced by unexpected events and continuous change of system operating conditions. In such systems, many uncertainties exist within the operation due to a large number of causes. These aspects makes it very challenging to effectively operate and control power systems in today's environment by relying solely on strict conservative mathematically formulated solutions. Therefore, adopting alternative theories, such as fuzzy set theory-based approach, can provide a complementary tool to mathematical approaches for solving power system problems. In comparison to traditional logic which uses variables that have precise values called "crisp" values, fuzzy logic assigns a "set" of values to the variables to account for imprecisions and uncertainties. Each value has a degree of membership of the set which represent the probability of the variable having that value. A membership function identifies the degree of membership over the range of possible values, known as the universe of discourse. This function can be defined to represent an adjective, known as a linguistic variables or fuzzy set, which describes the set of variables. The linguistic variables are variables whose values are words rather than numbers. This ability of using common linguistic terminology, that is easy to understand, allows fuzzy logic to model qualitative reasoning and to be used in knowledge representation. The advantages of using fuzzy logic or fuzzy set theory over conventional problem solving techniques can be summarised as follows [55], [56], [54] and [57] :

- Fuzzy logic uses natural language terms used by experts which are conceptually easy to understand.
- It is tolerant to imprecise data and can handle ambiguity.
- It can be built on top of the experience of experts, (i.e. it allows for incorporating the human experience in the design process).
- It can resolve conflicting objectives by designing weights appropriate to the selected objectives.
- It is flexible and relatively easy to implement.
- It can provide a smooth mapping between input and output data.
- Fuzzy rules can be tuned either on- or off-line.

- Fuzzy logic is capable of modelling nonlinear functions of arbitrary complexity. This makes it an appropriate alternative to linear theory of control design.
- Fuzzy logic does not necessarily replace conventional control methods; rather it can be blended with conventional control techniques. In fact it augments them, simplify their implementation and enhance their performance.

The fact that the basis of fuzzy logic theory is the basis of human communication underpins many of the other advantages of fuzzy logic. Because fuzzy logic is built on the structure of qualitative description used in everyday language, it is therefore easy to use, easy to implement and easy to tune. Also because experience and knowledge of experts are very important in power system operations, fuzzy logic is ideal and can be very effective for representing uncertainties and imprecisions in systems data by fuzzification of ambiguous variables and assigning membership functions based on preferences and experiences. It also remains possible to alter and adjust the fuzzy system's way of performance whenever new aspects are learned about the behaviour of the power systems which makes such systems adaptable and flexible.

6.3.1. Application of Fuzzy Logic in Power Systems

In recent years, fuzzy logic applications have received increasing attention in many areas of power systems. The objectives of these applications concentrate on the applicability of fuzzy logic to power systems for wider operating conditions and uncertainties. In the available literature, a number of distinctive areas in which fuzzy logic is been applied to demonstrate the advantages of fuzzy systems over conventional systems. These application areas can be classified based on the objectives of the fuzzy system as follows:

A. *Control*

Fuzzy logic control (*FLC*) is an area for which fuzzy set theory is used to model control decisions. In comparison with a conventional controller where the system is modelled analytically using a set of differential equations from which the control parameters are configured to satisfy the controller objective function, fuzzy logic-based controllers adjust the control parameters using a fuzzy rule-based expert system. For a fuzzy logic controller, choosing the appropriate variables as input and output signals for the controller is a critical task. Once input and output variables are chosen, it is required to decide on the linguistic variables which are used to transform the numerical crisp values of the input of the fuzzy controller to fuzzy quantities. The number of these linguistic variables influences the quality of the performance of the controller significantly. As the number increases, the computational time and memory requirements increases and, as always, a compromise has to be made to choose the number of linguistic variables. The use of fuzzy logic in the area of power system control is apparent in a number of applications such as [54], [58]:

1. Fuzzy logic-based power system stabilisers.
2. Automatic generation control (*AGC*)/ load frequency control (*LFC*).
3. *FACTS* devices control.
4. Reactive power/Voltage control.

As any form of control category, fuzzy system applications in the area of power system control aim to provide and satisfy a number of objectives. The objectives of fuzzy logic control *FLC* in power system can be summarised in the following [56]:

1. To improve the control task performance and make it adaptable, flexible and more robust.
2. To provide a way of expression of non-linearities and uncertainties in power systems.
3. To allow for expert and operators experience to be implemented since heuristic and expert knowledge are essential in power system operation and control.
4. To improve cooperation between various controllers and allow for multi-objective coordination.

B. *Planning, Operation and Optimisation*

The issues associated with power systems planning and operation tasks are decision making and optimisation problems. It is a fact that power systems are large interconnected systems which are generally spread over wide geographic areas. Giving the circumstances in which such complex systems operate including deregulation, privatisation, and the competitive market environment, minimising cost of operation while maintaining high standard of security, reliability and quality of supply are important and critical tasks that need to be satisfied. In tasks where minimising costs and increasing system reliability form the main objectives, uncertainties arise and system constraints are not always well-defined. An example to this is the optimal power flow problem where constraints include generator and load bus voltage levels, line flow limits, and reserve margins. Such constraints are ambiguous and the objectives are not well-defined. In such cases, fuzzy set theory can provide a better solution to that provided by traditional approaches. The use of fuzzy logic theory in the area of power system planning, operation and optimisation can be seen in some applications including [54], [58]:

1. Optimal power flow.
2. Generator maintenance scheduling.
3. Unit commitment.
4. Load forecasting.
5. Power system stability analysis (contingency analysis).
6. Voltage security analysis (reactive power/voltage control).
7. State estimation.
8. Security assessment.
9. Power system reliability evaluation.
10. Economic dispatch.

The objectives of the application of fuzzy set theory in the areas of power system planning and operation where decision making and optimisation related problem make up the main issues can be summarised as follows [54], [56]:

1. To achieve flexible and robust planning.
2. To provide a way of expression of uncertainties in power system.
3. To provide a way of expression of probabilities (such as in the case of contingency analysis and stability evaluation).
4. To improve accuracy as in load forecasting.
5. To reduce computation time.
6. To provide an expression of experience based rules.

C. *Protection and Diagnosis*

Reliable operation of power systems relies primarily on properly functioning and maintained equipment. Preventing equipment failure from damage caused by faults and disturbances in the system depends on designed protective and relaying schemes. In protection systems, various relaying signals such as currents, voltages and line parameters are determined with a degree of approximation. This approximation results in inaccuracy which can prove costly during sever faults in the system. Also fault diagnosis can be a difficult task during multiple faults and relaying equipment failure. Failure of protective relays or circuit breakers results in uncertainties and inaccuracy of decision-making process. In such cases fuzzy logic can be suitable to deal with these uncertainties and be very effective in enhancing the accuracy of protection schemes [54].

In conclusion, fuzzy logic theory can handle approximate information and system uncertainties in a systematic way. Therefore, it is ideal for dealing with system nonlinearity and modelling complexity where inexact model exists or where ambiguity is common. As for power systems, fuzzy logic can provide an appropriate alternative technique to develop solutions to various problems related to control and operation of these systems. In the following section, the focus is put on utilizing fuzzy set theory in the area of power system control. A particular are of interest is using fuzzy logic theory to develop stability control scheme to enhance system stability and allow for better system utilization.

6.3.2. Fuzzy Logic based Power System Stabilisers FPSS

Power system stabilisers *PSSs* are the most cost-effective and widespread method of enhancing power system oscillation damping and improving overall system stability. Conventional power system stabilisers (*CPSSs*) have been implemented on actual power systems for this purpose and have provided significant enhancement for the overall stability of power systems [17], [59]. However, as indicated previously (section 6.2), there is a number of limitations to these CPSSs such as their fixed parameters which are tuned to ensure optimal controller performance at a nominal operating point.

Consequently, *CPSSs* performance could degrade whenever their operating point is shifted from nominal. In order to overcome the disadvantages of the widely used *CPSSs*, alternative design techniques have, recently, received a considerable attention. As a result, fuzzy logic has emerged as a powerful tool in designing fuzzy logic based power system stabilisers (*FPSSs*). The reasons are that the application of fuzzy logic control (*FLC*) techniques seems to be most suitable in such circumstances when a well-defined control objective cannot be specified and the involved system is very complex or its exact mathematical model is not available. Fuzzy logic approach to control design is simple, better alternative to nonlinear control techniques, easy to understand, robust and have relatively low computation requirements. They also can be built on top of conventional controller to enhance the overall control performance.

Attempts to use fuzzy logic techniques to develop power system stabilisers are well-documented in the literature. In [60] and [61] the basic configurations of a fuzzy logic controller *FLC* is described. In comparison to the configurations of conventional control, in which the control process is expressed through a set of mathematical equations that determines the relation between specified numbers of data inputs, fuzzy logic control *FLC* design approach resembles that of a knowledge-based technique. Fuzzy logic controllers are basically rule-based controllers that utilise the principle of fuzzy set theory in its data representation and its logic. A typical structure of an *FLC* is shown in figure (6-3) [60]. The basic configuration of an *FLC* can be simply presented in four main parts. Those are input and output scaling factors, fuzzifier, de-fuzzifier, rule-base and fuzzy inference engine.

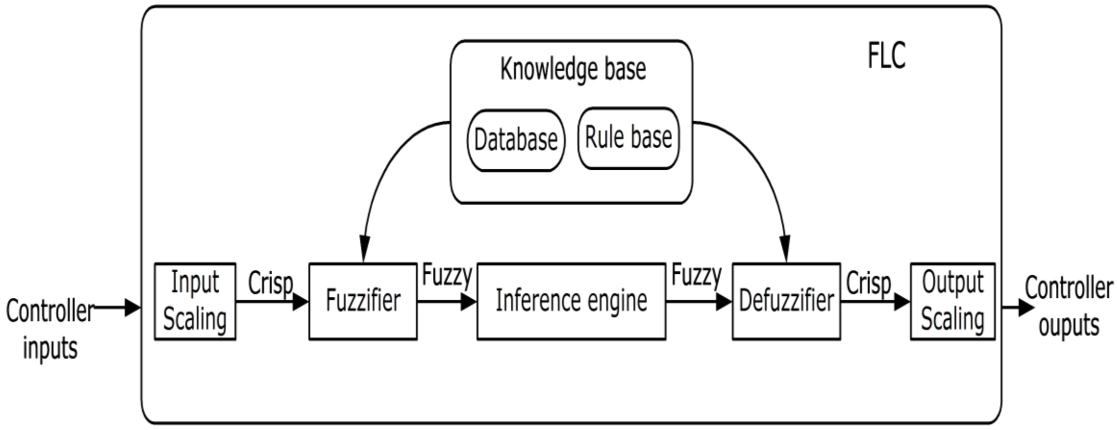

Figure 6-3: Basic configuration of Fuzzy Logic Controllers (FLC) [60]

A. *Fuzzification*

The fuzzification is a process by which the crisp input control variables are transformed into fuzzy linguistic variables using normalized membership function [62].

B. *Knowledge-base and Inference Engine*

The fuzzy logic inference engine is the part responsible for deducing the proper control action based on the available rule base. The knowledge base includes the definition of the fuzzy membership functions, defined for each control variable, and the required rules that determine the control action using linguistic variables. It enables the controller to map the input fuzzy sets to the output fuzzy sets through control rules in the form of *IF-THEN* statements. This part of the control design allows for incorporating the human experience in the design process as some of these rules can be derived based on past experience, knowledge acquired through off-line simulation, understanding of the dynamics of the involved system and common sense engineering judgment [63].

C. *De-fuzzification*

The de-fuzzification is a process by which the fuzzy linguistic output control action is transformed into proper crisp values using normalized membership function [62].

D. *Input and Output Scaling Factors*

The input and output scaling factors are important in order to allow for a wide range of operating conditions to be considered without having to consider the physical domain of the input and output signals [64]. As recommended in [65], the range of the membership function for all input and output signals should be kept between ± 1. Input scaling factors are therefore required to normalise the inputs magnitudes so that they are contained in the chosen range. Similarly, output scaling factor is required to de-normalize the output signal.

6.3.2.1. Design Procedure of Fuzzy Power System Stabilizer FPSS

Figure (6.3) shows the main components of a fuzzy logic based controller. However, for fuzzy logic based power system stabilisers *FPSSs*, the design process can be split into a number of steps as described below [60].

A. *Selection of Control Variables (Input and Output Signals)*

To design a fuzzy logic controller *FLC*, variables that describe the dynamic behaviour of the subject to be controlled should be chosen as input signals to the controller. It is a common practice to use the output error (e) and the rate of change or the derivative of the output (ė) as control inputs [60]. The input and output variables for an *FPSS* can be described as in equation (6.1).

$$X_j = \left\{ e, e^{\bullet}, u_{pss} \right\} \qquad (6.1)$$

In many cases of *FPSS* design, the generator speed deviation ($\Delta\omega$) and its derivative ($\Delta\acute{\omega}$), which resembles the acceleration, are considered as inputs for the controller [66], [67], [68],[69], [70] and [71]. In other applications, the speed deviation ($\Delta\omega$) and the active power deviation (ΔP_e) of the synchronous generator are chosen as input signals to the controller [61], [72], [73], [74], [75]. In both cases, normally two appropriate scaling factors are applied to the speed deviation and acceleration/active power deviation and then both control signals are fed to the *FPSS*. The output signal of the controller (u_{pss}) is also scaled using an output scaling factor and added to the *AVR* as a supplementary control signal.

B. *Membership Function Definition*

The measured crisp input variables are converted into fuzzy variables. The universe of discourse (i.e. the set that contains the entities over which certain variables may range [76]) of each fuzzy variable can then be quantised into a number of overlapping fuzzy sets known as linguistic variables. In practical applications, the universe of discourse is restricted to a small range (X_{min} , X_{max}) [60]. The number of the linguistic variables varies according the control application. Normally odd numbers are used (3, 5, 7 …). Higher number of linguistic variables results in an increase in the number of the rules required to fire the appropriate control action. In most *FPSS* applications, seven linguistic variables are chosen to represent the crisp input values by fuzzy sets. Those seven linguistic variables used to represent each input and output signals are (*NB*) negative big, (*NM*) negative medium, (*NS*) negative small, (*Z*) zero, (*PS*) positive small, (*PM*) positive medium and (*PB*) positive big. A membership function that maps the crisp values into fuzzy values is assigned to each fuzzy linguistic variable. A membership function can differ in shapes (i.e. triangular, trapezoidal, or a bell shape). For the application of *FPSS*, the most commonly used shape is the triangular shape shown in figure (6-4) [60].

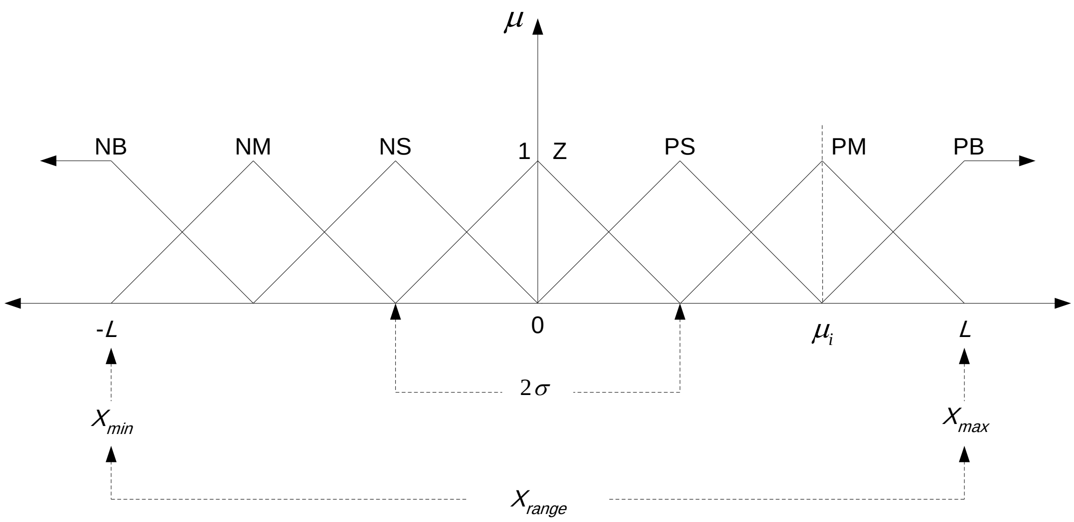

Figure 6-4: Triangular membership functions for FPSS input and output variables [60]

A triangular membership function of this configuration shown in figure (6-4) can be expressed by equation (6.2).

$$F_i(x) = \begin{cases} \dfrac{x-\mu_i+\sigma_i}{\sigma_i} & \text{for } \mu_i - \sigma_i \le x \le \mu_i \\ \dfrac{x-\mu_i-\sigma_i}{\sigma_i} & \text{for } \mu_i \le x \le \mu_i + \sigma_i \end{cases} \tag{6.2}$$

Where μ_i is the centroid of the i^{th} membership function and σ_i is a constant which identifies the spread of the i^{th} membership function [60].

For simplicity, the membership functions are assumed to be symmetrical and each one overlaps its adjacent function by 50% as shown in figure (6-4). By using membership functions of this type, the input variables can then be transferred into linguistic fuzzy variables. For practicality, the membership functions need to be normalized in the interval [-*L*, *L*], which is symmetrical around zero. For this particular reason, the control signal amplitudes are expressed in terms of controller parameters known as the scaling factors (gains) as shown in figure (6-3). The input and output scaling factors are important in order to allow for a wide range of operating conditions to be considered without having to consider the physical domain of the input and output signals. The scaling factors or the controller parameters can be defined as in equation (6.3) [60], [51].

$$K_j = \frac{2L}{X_{range_j}} \tag{6.3}$$

Where K_j is the input and output scaling factors and are referred to as the fuzzy logic controller parameters, X_{range_j} is the full range of the control variable X_j, which from figure (6.4), can be described as in equation (6.4).

$$X_{range_j} = X_{\max_j} - X_{\min_j} \tag{6.4}$$

Where $X_{\max_j}$, $X_{\min_j}$ are the maximum and the minimum values of the control variable X_j.

The parameters of the membership function (σ_i, μ_i) can be identified using the above definitions using equations (6.5) and (6.6).

$$\sigma_i = \frac{X_{range_j}}{n-1} \tag{6.5}$$

$$\mu_i = X_{\min_j} + (K-1)\times\sigma_i \tag{6.6}$$

Where i= 1,…….,n and n is the number of linguistic variables

C. *Rule-base and Inference*

The basics of fuzzy logic systems relies on a process of mapping an input fuzzy set to an output fuzzy set which forms the control action. This is acquired by a set of fuzzy rules which determines the relation between those fuzzy sets. The knowledge base and the inference engine shown in figure (6-3) are the parts responsible for this mapping process. The proper control action is deduced based on the available rule-base. The knowledge-base includes the definition of the fuzzy membership function defined for each control variable and the required rule that determines the control action using linguistic variables. This process of mapping the input fuzzy sets to the output fuzzy sets is achieved through control rules in the form of *IF THEN* statements. This part of the control design allows for incorporating the human experience in the design process as some of these rules can be derived based on past experience, knowledge acquired through off-line simulation, understanding of the dynamics of the involved system and common sense engineering judgment. For the design of fuzzy logic based power system stabilizers, techniques to derive and optimise the required rule-base are well-documented in [60] and [65]. The required number of rules depends on the number of the linguistic variables being assigned to each input variable. As indicated above, most FPSS applications use seven linguistic variables to represent the crisp input values by fuzzy sets (*NB, NM, NS, Z, PS, PM, and PB*). As a result, 49 (7×7) control rules are required to relate those control variables to each other. Table (6.1) provides a generic control rules for fuzzy controllers used as power system stabilisers [60].

Table 6-1: Decision table of fuzzy control rules for an FPSS

Speed deviation ($\Delta\omega$)	Derivative of speed deviation ($\Delta\acute{\omega}$) / active power deviation (ΔP_e)						
	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NM	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PM	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

The inference mechanism utilises the above table to determine the fuzzy set of the control action using *IF THEN* statements in the form "*if A, then B*," where *A* is the rule antecedent and *B* is the rule consequence. Every entity in table (6.1) represents a rule. The antecedent of each rule conjoins the two fuzzy input variables. The first input variable is the speed deviation ($\Delta\omega$) which represent the error (e) described by equation (6.1). The second input variable can be either the derivative of the speed deviation ($\Delta\acute{\omega}$) or the active power deviation (ΔP_e) which represent the derivative of the error ($\dot{e}$) shown in equation (6.1). An example to a randomly picked i^{th} rule is as in:

If $\Delta\omega$ *is NB and* ΔP_e *is NM then* u_{pss} *is NB*

Determination of the degree of membership of the output linguistic variable is done using what is known as *MIN-MAX* inference or the Mamdani type inference [65]. For clarity of explanation, figure (6-5) shows an example (adopted from [77]) for fuzzification of two input variables using membership function similar to that described in figure (6-4). In figure (6-5) bellow, the two input variables are the speed deviation $\Delta\omega$ and the active power deviation ΔP_e signals. As shown, the crisp value of $\Delta\omega$ is mapped into the *PS* and *PM* regions of the triangular membership function ($\mu_{\Delta\omega}(PS), \mu_{\Delta\omega}(PM)$), and is assigned a degree of membership equal to 0.8 and 0.2 respectively. Similarly, the crisp value of ΔP_e is mapped into the *NS* and *Z* regions ($\mu_{\Delta P_e}(NS), \mu_{\Delta P_e}(Z)$) and is assigned a degree of membership of 0.7 and 0.3 respectively.

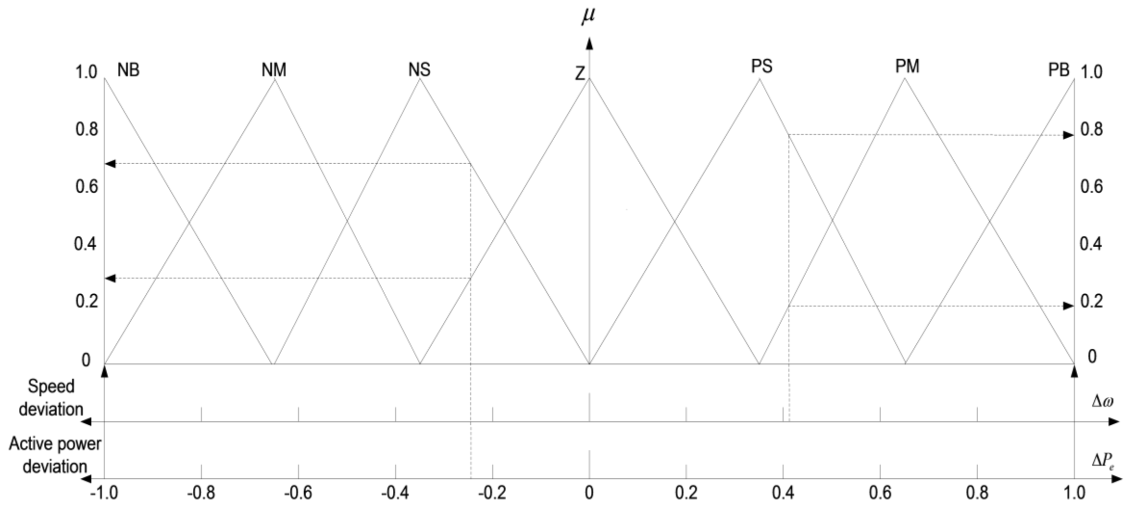

Figure 6-5: Example of fuzzification using triangular membership function (adopted from [77])

The rule-base shown in table (6.1) is used to firstly, determine the output decision as a linguistic output variable, and secondly, to assign a degree of membership or weight to the output linguistic variable. Applying table (6.1) to this example using the *IF-THEN* statement maps the output logistic variable into four regions (*Z, PS, PS, PM*) as shown below.

If $\Delta\omega$ *is PS and* ΔP_e *is NS then* u_{pss} *is Z*

If $\Delta\omega$ *is PS and* ΔP_e *is Z then* u_{pss} *is PS*

If $\Delta\omega$ *is PM and* ΔP_e *is NS then* u_{pss} *is PS*

If $\Delta\omega$ *is PM and* ΔP_e *is Z then* u_{pss} *is PM*

The degree of membership assigned for the output linguistic variable is then determined using what is known as *MIN-MAX* inference (it utilises the minimum function for the implication of the rule, while the combination of all rules is represented be the maximum function). The degree of membership for each output linguistic variable is given by the minimum of the degree of membership of the two input linguistic variables determining that output linguistic variable. For example, consider the first rule, (*If* $\Delta\omega$ *is PS and* ΔPe *is NS then upss is Z*), the membership of the output linguistic variable (*Z*) is determined as in equation (6.7) [51].

$$\mu_{out}(Z) = \min\left[\mu_{\Delta\omega}(PS), \mu_{\Delta P_e}(NS)\right] \qquad (6.7)$$

Applying this technique, the degree of memberships for all outputs can be determined as shown in table (6.2).

Table 6-2: Example of rules activation in a fuzzy system

Δω	ΔP_e						
	NB	NM	NS (0.7)	Z (0.3)	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NM	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS (0.8)	NM	NS	Z (0.7)	PS (0.3)	PM	PM	PB
PM (0.2)	NS	Z	PS(0.2)	PM(0.2)	PM	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

The output of the inference process at this stage is a fuzzy set. Once the memberships of all output linguistic variables are assigned, a crisp discrete output is derived based on de-fuzzification techniques which form the last step of the design procedure.

D. *De-fuzzification strategy*

De-fuzzification is the process by which a fuzzy controller produces its desirable crisp numerical output from a fuzzy set of linguistic variables. As in the example above, if two or more degrees of memberships are assigned to the same linguistic variable (i.e. *PM* is assigned both 0.2 and 0.3) then the maximum of the weight is associated with the linguistic variables (hence, *MIN-MAX* inference). By using these linguistic variables and membership functions, an area can be formed as shown in figure (6-6). The centre of gravity (also known as the centroid method) of the mapped area is then used to infer the crisp output value. The centre of gravity method can be described by the following equation [51].

$$u_{pss} = \frac{\sum_{i=1}^{Rules} u_{out}(Z)\,\mu_{out}^{i}(Z)}{\sum_{i=1}^{Rules} \mu_{out}^{i}(Z)} \qquad (6.8)$$

Where u_{pss} is the controller crisp output value, and $\mu_{out}^{i}(Z)$ denotes the output membership degree for the i^{th} rule associated with the output subset of Z, $u_{out}(Z)$.

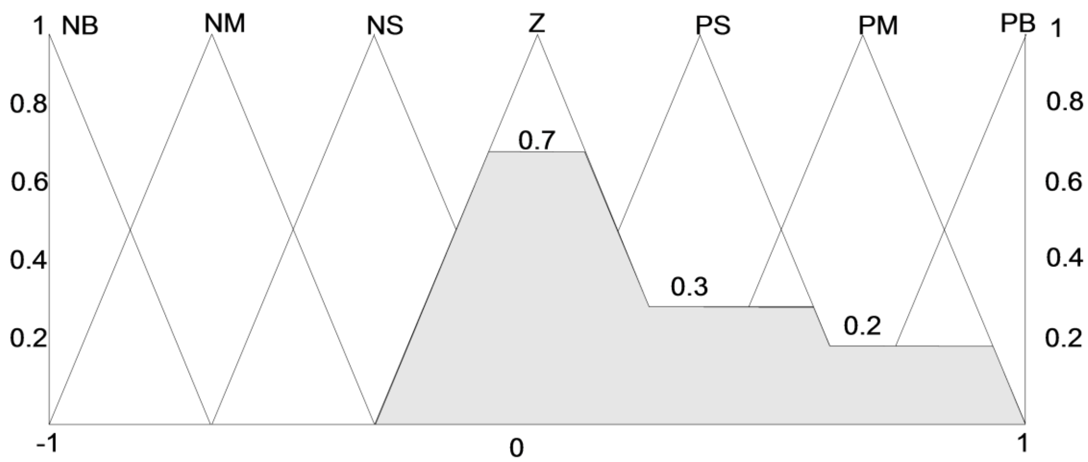

Figure 6-6: Example of de-fuzzification of output signals (adopted from [77])

In other words, the centre of gravity method is used to compute the centre of the area encompassed by the fired rules in the knowledge base part of the controller which results in a single crisp value that represent the controller output signal.

6.3.2.2. Enhancement of FPSS Performance

The feasibility of fuzzy logic based power system stabilizers *FPSSs* as stability enhancement schemes has been demonstrated in a considerable amount of research article. Fuzzy logic based techniques has been suggested as a possible solution to overcome the problems and drawbacks associated with conventional power system stabilizers *CPSSs,* discussed earlier in section 6.2. Thereby using fuzzy logic techniques, complex system mathematical models can be avoided while providing good performance under different operating conditions. Fuzzy logic is proved to have the features of simple concept, easy implementation and computational efficiency, all of which are important aspects of overall enhanced system performance.

Most of the early attempts to implement fuzzy logic technique to design *FPSSs* are focused on developing decentralised controllers local to the specific plant or generator. In [78], a controller that uses two real-time measurements of generator speed deviation ($\Delta\omega$) and the acceleration or the derivative of the speed deviation ($\Delta\acute{\omega}$) as input signals is developed based on simple fuzzy set theory [60]. Since only local measurements are required by the developed *FPSS* on each generating unit, the stabilizer is of a decentralised output feedback form of control and is easy for practical implementation. It is also intended for multi-machine power system and the results obtained showed a good dynamic performance over a range of operating scenarios. Reference [79] introduces an *FPSS* that uses speed deviation ($\Delta\omega$) and power output deviations (ΔP_e) of the local machine as the input variables for the fuzzy logic controller. The developed controller performs the function of a power system stabilizer and provides a supplementary control signal to the excitation system of the generator. The proposed *FPSS* is developed for a single machine and procedures in the development of its structure and rule base and the tuning of its parameters is described. The proposed tuning methodology is based on an off-line process that adjusts the controller parameters based on specified performance characteristics for the controlled system.

The test results showed robust performance and effectiveness under various operating conditions and disturbances. A similar design approach is described in [61] where speed deviation ($\Delta\omega$) and accelerating power (ΔP) are used as input signals to the controller. The developed *FPSS* is tested in a multi-machine power system environment in which the tuning of the *FPSS* parameters is automatically carried out off-line by using a tuning software extension module to the multi-machine simulation package. The tuning module hierarchically lies on top of the simulation package and uses a blind search algorithm to locate optimum or near-optimum controller gains that minimise certain system performance indices. The results obtained in [61] showed that the proposed *FPSS* can effectively damp both modes of oscillations (local modes and inter-area modes) in a multi-machine power system. The results also showed that the developed *FPSS* can work cooperatively with conventional stabilizers *CPSSs*. Reference [61] also emphasise the importance of the location of the *PSS*; it states that in order to provide efficient damping for both local and inter-area modes of oscillations, *PSS* have to be installed on generators which are the main cause of the two modes of oscillations. It also concludes that the lack of on-line complicated mathematical computations makes fuzzy logic based techniques more reliable for real-time applications where small sampling time may be required. In [80] an augmented *FPSS* is proposed to enhance power system stability. The introduced controller utilises the fuzzy logic based stabilizer in the usual manner, similar to that in [78] described above in terms of input control variables. In addition it uses a modification of the terminal voltage feedback signal to the excitation system as a function of the accelerating power on the unit. The non-linear action of the proposed augmented *FPSS* increases the power system stability significantly while it is simple to implement. The test results showed that implementing the augmented controller in both single machine system and multi-machine power system results in an enhanced dynamic performance over a wide range of operating conditions. Article [68] provides a systematic approach to fuzzy logic control by which a design and analysis of an adaptive *FPSS* is demonstrated. The proposed systematic tuning methodology is intended to overcome the difficulties and drawbacks of manual tuning of control rules and membership functions adopted in previous design attempts. It assumes that while the quantity of the control law may change, its quality remains. Thus control rules and membership functions are designed once and then modified by systematic scaling techniques for a particular system and range of operating conditions.

The advantage of the proposed design approach is that the controller is insensitive to the precise dynamics of the system which gives it a degree of adaptability over a wide range of operating scenarios. The test results demonstrated the effectiveness of this design approach in developing a robust *FPSS* that is capable of system stability enhancement.

In [67] a design procedure for an *FPSS* is presented. Speed deviations and its derivative are chosen as the input signals to the controller. A new technique that uses a normalised sum-squared deviation (*NSSD*) index is utilised to determine the *FPSS* parameters and acquire a proper tuning. The proposed tuning methodology is an off-line process that adjusts the controller parameters by minimising a *NSSD* index evaluated for rotor angle of pre-identified critical machine. The determination of the critical machine to which the *FPSS* is assigned is achieved using the well-known concept of participation factors [20] which are computed from the right and left eigenvectors of the system state matrix of the power system. By using Eigen structure analysis, the oscillatory rotor modes are identified first. Secondly, by comparing the participation factors of the speed component of all the machines in the poorly damped rotor mode, the machine with the highest participation factor is identified as the critical machine. The simulation results showed the effectiveness of the response of the designed *FPSS* to various disturbances in a multi-machine power system environment. It is also seen from the results that the *FPSS* can damp both local and inter-area modes of oscillations effectively as well as having a wider stable region with comparison to *CPSS*. An interesting design technique is introduced in [81] which proposes a fuzzy logic-based adaptive power system stabiliser for a multi-machine power system. The proposed design approach accommodates two linear conventional stabilizers and a fuzzy logic-based signal synthesizer. The two linear stabilizers are designed based on the traditional frequency domain method for extreme loading conditions which allow them to generate stabilizing signals working best under these conditions. The fuzzy-based synthesizer then combines the two individual signals in such a way that the signal fits the loading condition optimally. The fuzzy controller is optimised using a least squares error criterion and is tested for a single machine infinite-bus as well as for a multi-machine system. The results showed that the proposed *FPSS* provides adequate and satisfactory damping for low frequency oscillations under a wide range of operating conditions and can perform better than conventional stabilizers. Reference [66] introduces a modified method for designing fuzzy logic based power system stabilizers to counter the small signal oscillatory instability in power systems. The modified technique alternatively represents the two states of the generator $\Delta\omega$ (speed deviation) and $\Delta\acute{\omega}$ (acceleration), which form the stabilizer input signals, in polar form and generate the stabilizing signal based on the magnitude and angle of those signals. The designed stabilizer is shown to be easier to implement in a multi-machine system and quite effective in damping both local and inter-area modes of oscillation. A variable structure adaptive fuzzy logic based power system stabilizer (*AFPSS*) is proposed in [75]. The proposed controller is a fuzzy logic based stabilizer that has the capability of adaptively tune its rule base on-line. The proposed controller is initialized using the rule base of a standard *FPSS* to ensure an acceptable performance during the learning stages. The rule base is then tuned on-line so that the stabilizer can adapt to and cope with different operating conditions. The alterations and changes in the fuzzy rule base are carried out using a variable structure direct adaptive control algorithm to achieve the pre-defined control objectives. The use of such adaptive algorithm has the advantages of, firstly achieving a good performance in the training stage as it makes use of the initial standard rule base of *FPSS*, and secondly providing a robust estimator since it depends on a variable structure technique. The adaptive feature of the proposed controller results in an improved performance as it significantly reduces the rule base size and maintains satisfactory operation. This is confirmed by simulation results of a single machine and a multi-machine power system showing the effectiveness of the proposed *AFPSS* in damping power system oscillations. A systematic approach for the design of an *FPSS* is presented in [82] which have the potential to shorten the tuning process of fuzzy rules and membership functions. The proposed technique breaks the design process into two stages. In the first stage a proportional derivative type PSS (*PDPSS*) is developed. In the second stage, this *PDPSS* is transformed into fuzzy logic stabiliser *FPSS*. Because this approach is systematic and straightforward, it provides an easy and reliable scheme to overcome the drawbacks of other methods used to tune the fuzzy controller parameters and rule base such as trial and error methods or the use of searching algorithms such as genetic algorithms (*GA*), which can be time consuming. Simulation results on a multi-machine power system showed the technique to be effective in designing robust *FPSS* that is capable of providing adequate damping for power system oscillations

R. Gupta in [83] discusses a study of fuzzy logic power system stabilizer (*FPSS*) for stability enhancement of multi-machine power systems. The proposed stabilizer uses a reduced rule base limited to 25 decision rules (5×5), which relates the input control signals (speed deviations $\Delta\omega$ and acceleration $\Delta\acute{\omega}$) to the deduced control action. Instead of using the extended standard 49 decision rule table shown in table (6.1), reference [83] uses less membership functions and therefore less rules to achieve the controller objectives. Also different de-fuzzification methods were used to quantify the fuzzy output signal. This is found to have reduced the computation requirements while maintaining satisfactory performance. Test results in a small two-area four-machine system were quite encouraging and satisfactory. In [70] the performance of a hierarchical *FPSS*, which is tuned automatically as the operating conditions of power systems change, is evaluated by applying it to a multi-machine power system. Similar to other fuzzy logic based stabilizers the proposed *FPSS* uses the speed deviation ($\Delta\omega$) and its derivative ($\Delta\acute{\omega}$) as input signals. A function of adaptability is introduced into the design by means of two scaling parameters which have the ability to adjust their values as system conditions change. These scaling parameters are the output of another fuzzy logic system (*FLS*), which acquire its inputs from the operating conditions of the power system. In order to tune the *FPSS*, the two scaling factors are used to adjust the range of inputs as operating conditions change (input signal 1= $K_p\ \Delta\omega$ and input signal 2= $K_d\ \Delta\acute{\omega}$). The *FPSS* is tuned by computing optimum input scaling factors (K_p) and (K_d) using another *FLS* that uses the electrical active power (P_e) and reactive power (Q) of each machine as input signals to represent the operating conditions of each machine. The *FLS* with two inputs (P_e and Q) is referred to as the tuner and the proposed scheme is referred to as the self-tuning fuzzy logic power system stabilizer (*TFPSS*). This process of tuning the *FPSS* makes it adaptive to changes in the system operating conditions and allows for an enhanced overall system performance. Simulation results showed that by using the proposed mechanism to tune the *TFPSS* on-line, better response of the system can be achieved in a wide range of operating conditions compared to fixed parameter *FPSS* and conventional *CPSS*, with the latter still the less efficient of all. In [69] an alternative new approach for designing *FPSS* that utilises a genetic and evolutionary algorithm (*GEA*) to optimise the scaling factors of the controller is proposed. In this design approach the scaling factors or the controller parameters are referred to as the normalisation and de-normalisation factors and the study is carried out considering an *FPSS* based on 3, 5 and 7 membership functions (*MFs*) of Gaussian shape. The objective of the proposed design is to obtain an *FPSS* which improves both transient and small signal stabilities of power systems and investigate the effect of variation of a number of linguistic variables (membership functions) on the performance of *FPSS* in order to obtain an optimum *FPSS* design with a minimum number of *MFs* without jeopardizing the dynamic performance of the system. The proposed design technique uses a conventional *PSS* to examine the dynamic response of the system under study for different operating conditions and obtain the maximum values of the input signals $\Delta\omega$ and $\Delta\acute{\omega}$. Based on these observations, initial values for the input scaling factors (normalisation factors) are set. These values are considered as upper bounds of the input scaling factors ($K_{\Delta\omega}$ and $K_{\Delta\acute{\omega}}$) for further optimisation of these values using *GEA*. The upper bound of the output scaling factor (de-normalisation factor) is set initially to equal 1. Once those values are chosen, an algorithm for optimising the normalisation and de-normalisation factor using *GEA* is used to optimise them. Simulation results of the proposed design showed a robust performance of the *FPSS* for various operating conditions including small and large disturbances. It also indicates that there is no merit in increasing the number of *MFs* beyond 5.

A simplified fuzzy logic controller (*SFLC*) with a significantly reduced set of fuzzy rules, small number of tuning parameters and simple control algorithm and structure is described in [84]. The technique takes advantage of the symmetrical form of the rule base commonly used in fuzzy control applications, as that shown in table (6.1). According to [84], it is observed that, in the two-dimensional phase-plane, the required control action magnitude deduced from the rule base is the same for both negative and positive stabilising conditions and is proportional to the distance from the state of the system to the switching line (defined by the desired zero consequence). Based on this a simplified version of rule base is derived and a simplified fuzzy controller (*SFLC*) with the same performance but reduced rule base is proposed. Based on the *SLFC* a simplified power fuzzy logic power system stabiliser (*SFLPSS*) is designed and applied to a single machine-infinite bus system. The performance of the proposed *SFLPSS* is analysed over various load levels of the generating unit and different type of disturbances. Simulation results showed that a *SFLPSS* with only four rules can provide the same response as a standard *FPSS* with the original and complete rule base. Also compared with a *CPSS*, the proposed stabiliser showed an improved response and effectiveness in damping power system oscillations, although, it has not been tested on a multi-machine power system. An improved version of the self-tuned fuzzy logic power system stabilizer (*STFLPSS*), which follows the same design approach as the previously described one, is studied in [85] and is implemented in a computer simulations of a multi-machine power system. In addition to the advantages of the *SFLPSS* described in [84] (i.e. significantly reduced and one-dimensional rule table, small number of tuning parameters, simple control algorithm and simple architecture and control design), the latter [85] is able to non-linearly change, on-line, the sensitivity of the controller to the input signal which allows it to provide improved control performance over a wide range of changeable operating conditions, as the simulation results illustrated. In another attempt to introduce robustness and adaptability into the control design, T. Hussien in [86], describes a robust adaptive fuzzy controller as a power system stabiliser (*RFPSS*) used to damp inter-area modes of oscillations. The proposed approach uses a particle swarm optimisation algorithm to tune the controller input and output gains such that the sum square of the speed deviations is minimised. This introduces adaptation capabilities into the controller and allows it to cope with a wide range of operating conditions. The robustness of the design is assured by using fuzzy logic to compute the nominal values of the system non-linearities. Based on these values, conventional feedback linearization is modified to ensure robustness and acceptable performance. Simulation results of a four-machine two-area test system illustrated the enhanced performance of the proposed *RFPSS* compared with *CPSS*. A similar design approach is adopted in an earlier research [87] to develop an indirect variable structure adaptive fuzzy logic controller as a power system stabilizer (*IDVSFPSS*) used to damp inter-area modes of oscillation following disturbances in power systems. The designed stabilizer uses the speed and the speed deviation, obtained on-line and assumed to be measured from the output of the plant, as input signals. The output of the fuzzy identifier is the estimate of the unknown non-linearities of the model and is used as a feedback linearization framework to provide the necessary damping requirement to the power system. The design approach also uses practical swarm optimisation based algorithm to tune the controllers parameters (gains) such that the sum of the squares of the speed deviations is minimised. Item [88] inspects three types of fuzzy control algorithms in the case of a single machine connected to the network. It introduces two types of single-input/single-output control scheme and a third two-input/single-output control scheme, all of which are designed based on fuzzy logic techniques. The study shed lights on the importance of choosing the input control signals and how that might influence the controller performance. The results confirmed that considerable improvement of the system stability is achieved when using two-input/single-output control scheme with comparison to single-input/single-output control scheme. It also concluded that, although the design of the proposed *FPSS* is simple and requires no mathematical model of generator and power system, as would be the case for *CPSS*, the overall performance of the system is enhanced over a wide range of operating conditions and in the presence of different disturbances, small and large.

As described above, many attempts to design effective decentralised fuzzy logic based power system stabilizers (*FPSSs*) are well-documented in the literature. Great deals of these attempts were successful in developing control schemes that are sufficient and feasible. Clearly the superiority of fuzzy logic as a design tool to deal with the non-linearities in power systems when it comes to *PSS* design is shown. The performance of fuzzy logic based power system stabilisers (*FPSSs*) as local damping controllers is superior to that of conventional stabilisers (*CPSSs*) which are designed based on the traditional linear design approach. Nonetheless, these decentralised controllers remain local control schemes which act upon local control signals. Local control signals maybe sufficient enough in observing local modes of instabilities that results from local oscillations at the local plant. Wide area instabilities such as inter-area oscillation modes can be very difficult to be observed effectively in local signals. As bulk power transfers are being exchanged between interconnected areas in complex modern power systems, the need to deal with the rapid increase of inter-area oscillations has become essential to enhance power systems' stability, security and reliability of supply to meet customers demand. Regardless to the design technique used to develop local power system stabilisers (*LPSSs*), they have inherited limitations in damping inter-area modes of oscillations due to lack of information and observability to this phenomenon. Inter-area modes of oscillations are not highly observable and controllable in local signals as in the case of local modes of oscillations [89], [63]. Due to this lack of system wide view for *LPSSs*, their performance may not be as strong and reliable to damp inter-area modes of oscillations especially during sever disturbances. To ensure small signal stability [6] of power systems, increasing interest has been focused on developing wide-area based power system stabilisers (sometimes referred to as supervisory power system stabilisers (*SPSSs*) [31], [89]) by means of remote feedback control signals to wide-area based designed controllers. The advance technology in phasor measurement units *PMUs* has facilitated this and has allowed for increasing attempts in developing global controllers using wide-area measurement systems *WAMS*.

In section 3.2, some of these attempts are described based on the control strategy used to develop the control scheme. In the following section, a novel design for a wide-area based fuzzy logic power system stabiliser is introduced. The architecture and the basic design of the proposed wide-area based stabiliser are described. The performance of the proposed scheme is then tested by implementing it in a number of study cases through computer simulations. The scheme is referred to as **G**lobal **F**uzzy logic based **P**ower **S**ystem **S**tabiliser (*GFPSS*). The use of fuzzy logic as a tool to design the proposed controller is justified by the proved abilities and capabilities of fuzzy logic in providing very good and efficient stability enhancement schemes, as discussed previously in this chapter.

6.4. A Novel Design Structure for Wide-area based Fuzzy Logic PSS

This section describes the development of a fuzzy logic based power system stabiliser, designed to assure power systems stability and enhance transfer capabilities under stressed operation conditions. The principle of fuzzy logic control design described earlier in this chapter is adopted to develop the new stabilising control scheme. The design (as will be discussed in details later) introduces a new control loop to the traditional stabilising control loop used in the excitation/PSS control scheme. The newly designed control loop represents a wide-area based global fuzzy logic power system stabiliser (*GFPSS*). At first, the proposed controller is designed for a two-area test system to simplify the design procedure. The structure and the design is then generalised to allow for implementations in multi-machine/multi-area power systems.

6.4.1. Structure of the Proposed Controller

The idea of the proposed control scheme is to provide a supplementary control signal in addition to the conventional *PSS* stabilising control loop found on any typical excitation control schemes of power generation units. The additional control loop, however, is designed based on fuzzy logic techniques and is developed to produce its control signals by processing wide-area based feedback control signals acquired from remote areas of the power system. This idea is illustrated in figure (6-7) which shows the general structure of the control scheme.

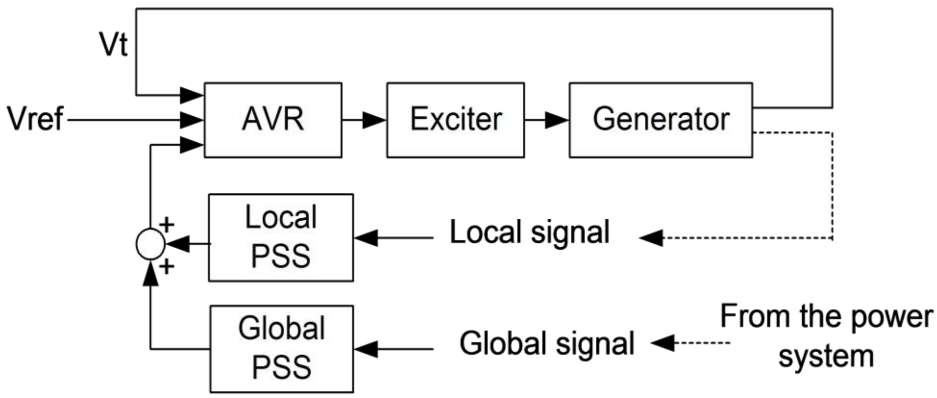

Figure 6-7: General structure of the proposed stability enhancement control scheme

The local control loop is the traditional *PSS* loop in which either a *CPSS* or an *FPSS* can be implemented to represent the local stabiliser *LPSS*. The global control loop is the wide-area based stability enhancement control loop in which the global fuzzy logic power system stabiliser (*GFPSS*) is allocated. The wide-area based control signals and the control design architecture is proposed as follow:

The *GFPSS* is proposed to be implemented for each two coherent, yet connected, areas within the power system. Techniques to identify coherent areas and key areas for wide-area based control, discussed in chapter 4 and 5 of this thesis, are for a significant importance to implement such a control scheme [50], [90]. For ease of description, the general design architecture is shown in figure (6-8) for the proposed controller with its signal acquisition system which is based on *WAMS*. The structure is proposed for two coherent connected areas A_i and A_j, which will be generalised on a later stage to be suitable for implementation in multi-area power systems.

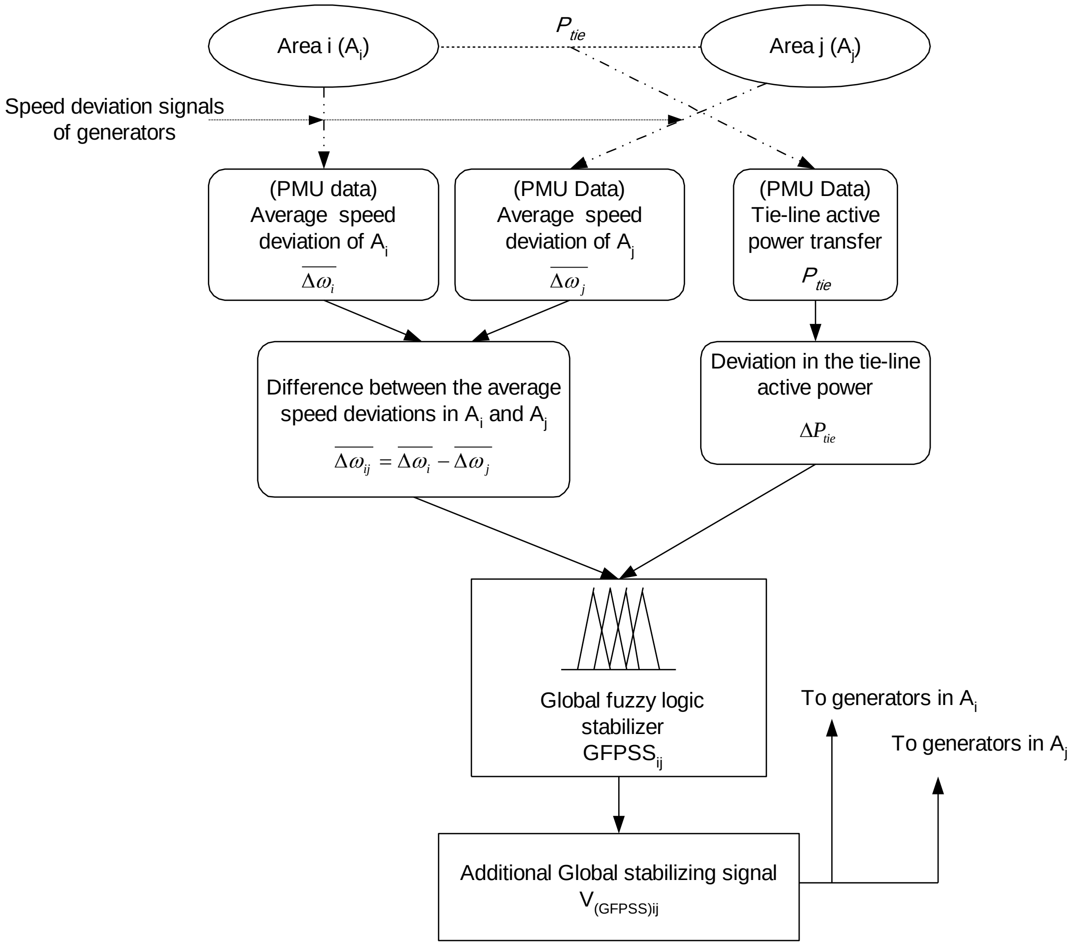

Figure 6-8: Design architecture of the GFPSS for two-area system

The proposed *GFPSS* is a two-input/single-output wide-area based controller. The two input signals for the *GFPSS* are extracted from measurements acquired from two coherent, yet connected, areas. The first input control signal to the *GFPSS* is the difference between the weighted average speed deviation signals of the two areas or clusters A_i and A_j, ($\overline{\Delta\omega_{ij}}$), of synchronous generators. The second input control signal is extracted from measurements of the active power transfer across the tie-line (P_{tie}) connecting both coherent areas A_i and A_j, namely, the deviation in the tie-line active power transfer (ΔP_{tie}). Once these wide-area signal measurements are available, they are fed into the fuzzy logic stabilising controller $GFPSS_{ij}$ of areas A_i and A_j to provide additional stabilising signals ($V_{(GFPSS)ij}$) to the generators involved in those areas as illustrated in figures (6-7) and (6-8) above. The acquisition of the two input control signals (i.e. the difference between the weighted average speed deviation signals of the coherent areas and the deviation of the active power transfer between the areas) is obtained as described in the following.

A. *Calculation of Weighted Average Speed Deviation of Generator's Clusters*

From measurement of speed signals or speed deviation signals acquired for a cluster (*i*) of synchronous generators within a large power system, a weighted average speed deviation of that cluster can be obtained using these signals and nominal powers of the machines in the considered cluster as shown by equation (6.9).

$$\overline{\Delta\omega_i} = \frac{\sum_{m=1}^{N_i} \overset{i}{\underset{m}{S}} \, \overset{i}{\underset{m}{\Delta\omega}}}{\sum_{m=1}^{N_i} \overset{i}{\underset{m}{S}}} \qquad (6.9)$$

Where:

$\overline{\Delta\omega_i}$ is the weighted average speed deviation signal of cluster *i*

$\overset{i}{\underset{m}{S}}$ is the nominal power of generator *m* in cluster *i*

$\overset{i}{\underset{m}{\Delta\omega}}$ is the speed deviation signal of generator *m* in cluster *i*

N_i is the number of generators in cluster *i*

The difference between the weighted average speed deviation of the two clusters *i* and *j* can then be calculated as in equation (6.10).

$$\overline{\Delta\omega_{ij}} = \overline{\Delta\omega_i} - \overline{\Delta\omega_j} \qquad (6.10)$$

The obtained signal is a wide-area remote feedback signal which has valuable information about the behaviour of remote generating units. This signal, when accompanied with the other remote control signal and then fed into the *GFPSS*, will allow the controller to have a wider view of the entire system and provide means of making a control action based on informative data about the entire system and not only the local unit.

B. *Calculation of the Deviation in Tie-line Active Power Transfer Between Two Generators' Clusters*

Inter-area oscillation modes are a wide area phenomenon in a power system which, in general, involves distinctive areas within the power system that oscillate against each other. It is essential for stable and secure operation to provide proper damping for these oscillations. To provide adequate damping for this phenomenon it is vital that, whatever control signals are used by the damping controllers, they should have a high observability characteristic of these oscillations. Since the phenomenon is of an inter-area nature and, in general, occurs between widely spread interconnected areas within the power system, the oscillation modes are highly observable and controllable in signals acquired from tie-lines connecting those oscillating areas. The active power transfer across tie-lines connecting coherent connected areas can carry significant information about inter-area oscillation modes. Hence, signals derived from active power transfer across transmission lines between interconnected areas (deviations in the tie-line active power transfer ΔP_{tie}) are used as the second input for the proposed *GFPSS*. The deviation in the tie-line active power transfer ΔP_{tie} can be derived from two successive measurements of the actual active power transfer across the tie-line (P_{tie}), separated by a sampling time period T as in equation (6.11). The equation is an adoption to the one used in [80], [83] and [69] to derive the acceleration signal from speed signal measurements at two sampling instants.

$$\Delta P_{tie} = \frac{\left[P_{tie}(KT) - P_{tie}(K-1)T\right]}{T} \qquad (6.11)$$

Where:

ΔP_{tie} the deviation of tie-line active power transfer

P_{tie} is the tie-line active power transfer

T is the time sampling period

K is the sampling counter

Having obtained the two required remote feedback signals, they therefore can be fed into the controller which, based on the available control algorithm, deduces a continuous control action. This additional wide-area based supplementary control action is added to the local stabilising control, provided by the local *PSS,* such that both stabilising signals are used to alter the actions of generators' excitation systems in an effective way to assure system stability, increases system reliability, and allow for better utilisation of systems' assets.

6.4.1.1. Implementation of the Proposed GFPSS in a Two-area System

As indicated previously, the design process is aimed first for a simple two-area system to simplify the procedure and allow for easier generalisation for the design on a later stage. For that, the four machines two-area Kundur test system is used to demonstrate the implementation of the proposed design using computer simulation. The test system consists of two coherent areas connected through two 230kV transmission lines. The system is ideal to study electromechanical oscillations in interconnected power systems. Despite its small size, it mimics very closely the behaviour of a typical system in real world operation. In addition, the two areas are fully symmetrical coherent areas which make the system ideal for implementing the proposed scheme. Figure (6-9) shows the system single line diagram. The system data[3] and details can be found in [21]. The test system is set such that, at the local control loop level, three different PSSs are used to compare their performance. Two of those PSSs are conventional stabilizers designed based on the traditional linear design approach. This includes the MB-PSS with simplified setting according to the IEEE Std 421.5 [91] and the conventional Delta-w from [21]. The third PSS is a local fuzzy logic based power system stabiliser (LFPSS) designed based on fuzzy logic principles as described above. At the global control loop level a GFPSS is implemented between the two areas according to the structure shown in Figure (6-8). The additional wide-area based control signals are added to the excitation systems of the local units as shown in figure (6-7). The performance of the proposed scheme is tested for both small and large disturbances to illustrate the robustness of the controller [92]. The inclusion of a fuzzy logic based power system stabiliser at the local control level (LFPSS) is done merely to demonstrate the superiority of fuzzy logic based design approach over the conventional linear design technique using conventional power system stabilisers (CPSS). The design of both, the LFPSS and GFPSS, is carried out based on the procedures described in details in section 6.3.2.1.

[3] See also appendix A3

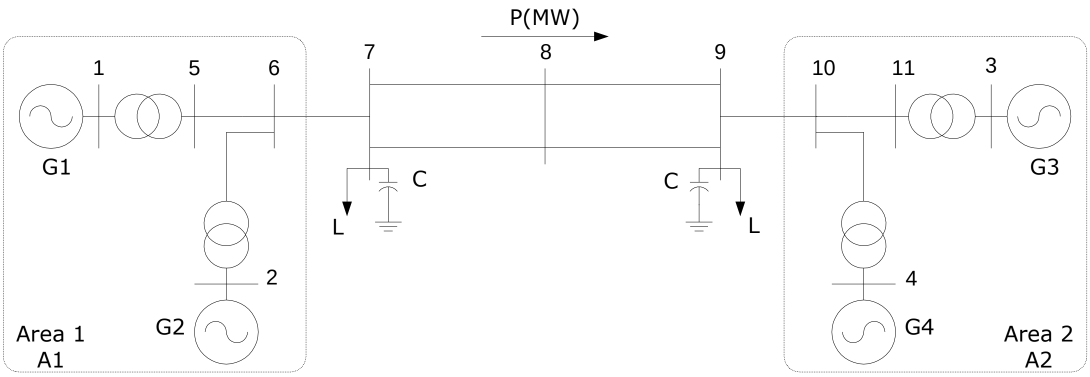

Figure 6-9: Four-machine two-area Kundur test system

6.4.1.2. Two-area GFPSS Performance Assessment and Discussion

In order to assess the proposed design, its operational performance during changing operating conditions of a power system is compared with that of other conventional power system stabilisers. The two-area study system described above is subjected to small disturbances and large disturbances while monitoring some quantities which depict the dynamic performance of the system, such as the active power flow in the tie-line connecting the two-area which gives a clear sight into the occurring oscillations between the two areas. Other monitored quantities are the speed deviation signals of the individual generators in the two areas. Such signals provide valuable information about the dynamic performance of the individual machines with regard to their involvement and participation in the oscillations.

A. *Performance during small disturbance*

For small signal disturbance, a pulse of 5% magnitude is applied for 12 cycles at the voltage reference of generator G1 in Area A1. Without any PSS involved in the control scheme, the system has an inter-area oscillation mode involving area A1 oscillating against Area A2. This mode is clearly observable in the tie-line active power transfer signal as shown in figure (6-10). The oscillation can be damped by including the PSS control loop into the control scheme. However, the effectiveness of the PSS in damping the oscillations differs according to the implemented PSS type.

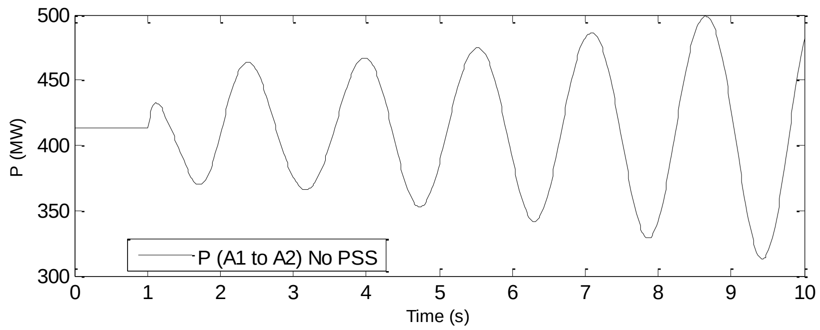

Figure 6-10: Active power transfer from A1 to A2 (NO PSS involved)

To allow for easy comparison, figures (6-11) and (6-12) show the system response to the disturbance. Figure (6-11) shows the system performance when using the MB-PSS and the LFPSS at the local control level with and without the GFPSS at the global control level. Similarly, figure (6-12) illustrates the performance of the Delta-w PSS and the LFPSS with and without the GFPSS.

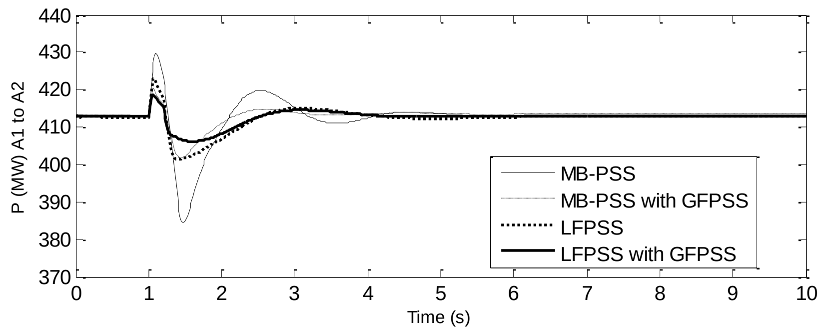

Figure 6-11: Active power transfer from A1 to A2 (with PSSs)

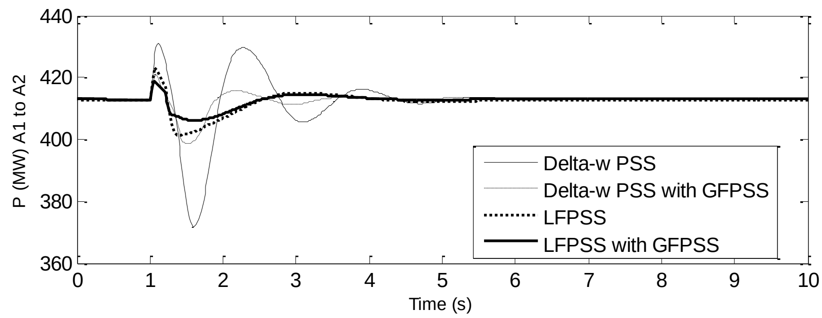

Figure 6-12: Active power transfer from A1 to A2 (with PSSs)

Referring to figure (6-11), clearly the MB-PSS stabilizers were able to stabilize the oscillating system. However, it is clear that when adding the global GFPSS loop to the local MB-PSS one, the system was able to retain stable operation conditions more effectively. Clearly, the added GFPSS loop provides more damping capabilities to the oscillation modes which results in smoother and fewer oscillations before reaching new stable operation conditions. From the same figure, the superior performance of fuzzy logic based PSS is clearly demonstrated. The performance of the LFPSS on its own (without the GFPSS) over performed that of the MB-PSS with the GFPSS combined together. This emphases the superiority of fuzzy logic based approach to the design of power system stabilizers over the traditional linear design techniques. The same argument is applied to figure (6-12). Clearly, best system performance is obtained when implementing global control loop in addition to the local one using fuzzy logic based power system stabilizers in both of them (LFPSS and GFPSS).

To understand how such an improvement in damping the oscillation in power transfer across the tie-line is achieved, figure (6-13) to figure (6-16) show the dynamic response of the individual generators in both areas to the encountered disturbance. The figures show the response of the generators while using different scenario of control (Delta-w PSS, Delta-w PSS with GFPSS, LFPSS, and LFPSS with GFPSS). Figure (6-13) shows the speed deviation of generator G1 in area A1. Generator G1 is the place where the disturbance occurred. Clearly, the deviation in the generator speed is settled more significantly when using LFPSS with GFPSS.

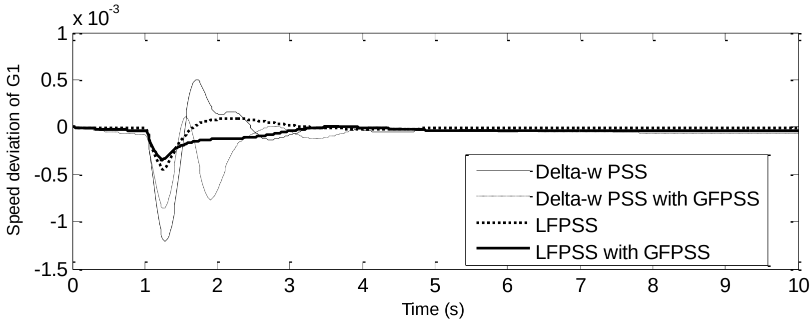

Figure 6-13: Speed deviation signals of G1 in A1

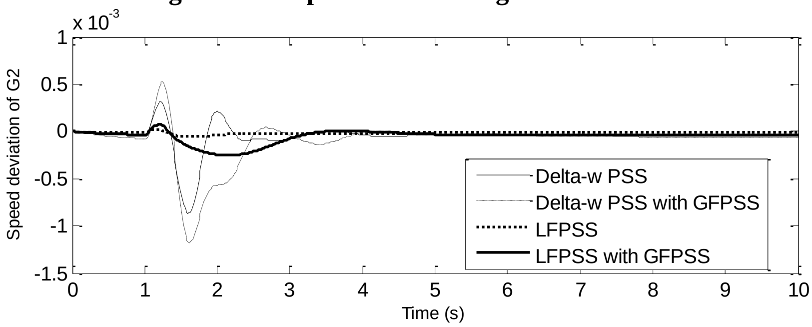

Figure 6-14: Speed deviation signals of G2 in A1

Figure (6-14), on the other hand, shows the speed deviation of generator G2 in area A1. As can be seen the speed deviation of this generator settled less rabidly when adding the

GFPSS to both the Delta-w PSS and the LFPSS. Figure (6-15) and figure (6-16) show the speed deviation of generators G3 and G4 in area A2 respectively. The response of these two generators is similar to that of G2 with regard to the implemented control scheme. This illustrates that, even though the speed deviation of the other generators in the neighbouring areas settled less rabidly when adding the global control loop to both local controllers (the Delta-w PSS and the LFPSS local control loops), the overall performance of the system is enhanced significantly (i.e. the added global control loop allowed the control system of the individual generators to have a wider view of the entire system). Therefore, the outcome of their control actions took into account what was going on in nearby areas.

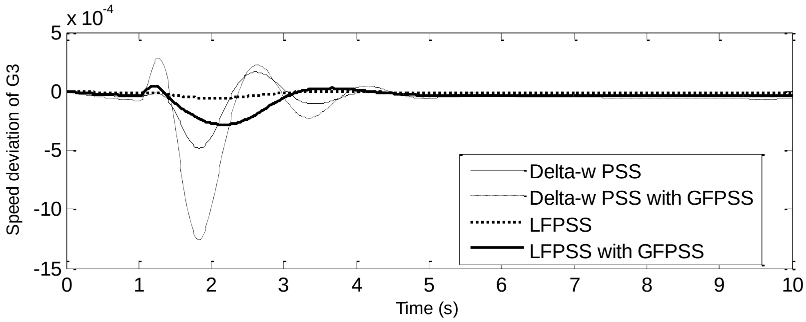

Figure 6-15: Speed deviation signals of G3 in A2

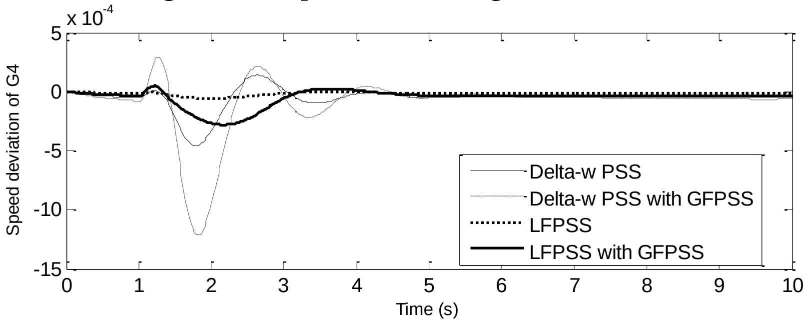

Figure 6-16: Speed deviation signals of G4 in A2

Though the clear result, from a wide-area system stability point of view, is that more enhanced system performance, robust coordination in performing control actions and improved transmission capability has been achieved.

B. *Performance during large disturbance*

In order to have a complete assessment of the performance of power system stabilizers, the robustness and the good performance during large disturbances and rabid changes in system operation conditions are other criteria that have to be investigated. Large disturbances such as faults in the system are common features in power systems. To test the proposed control scheme during such events, the system is subjected to a three phase fault of duration of 8 cycles in one of the transmission lines connecting area A1 and area A2. The fault is cleared by tripping the faulted line. The performance of the used controllers can be evaluated as shown in figure (6-17) and figure (6-18).

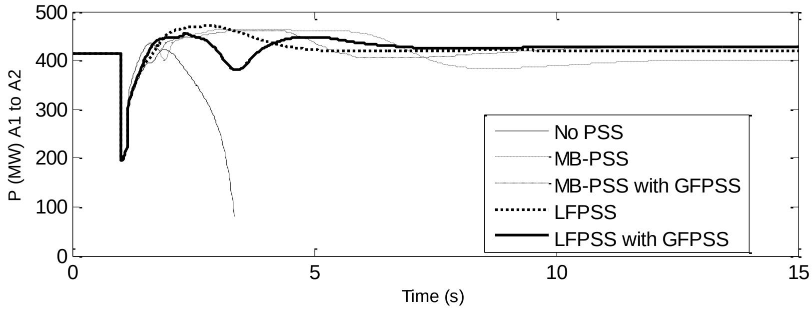

Figure 6-17: Active power transfer from A1 to A2 during three-phase fault with MB-PSS, LFPSS and GFPSS

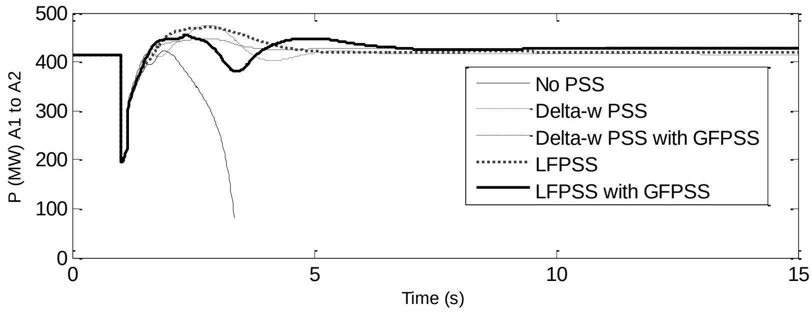

Figure 6-18: Active power transfer from A1 to A2 during three-phase fault with Delta-w PSS, LFPSS and GFPSS

Figure (6-17) shows the system response to the applied fault when no PSS is applied and when implementing the MB-PSS, the MB-PSS with the GFPSS, the LFPSS and the LFPSS with the GFPSS. The system will collapse if no PSS is implemented while the stabilizers succeed in maintaining system stability. Satisfactory performance of the proposed LFPSS with GFPSS is assured as the scheme enabled smooth transition between pre-fault and pos-fault conditions allowing the system to maintain stable equilibrium point of operation. Figure (6-18) shows the performance of the GFPSS when combined with the Delta-w PSS and the LFPSS. Clearly, the proposed scheme is robust and capable of providing proper control measures during large disturbances which makes it attractive for implementation in larger systems.

Adding the global control loop to include an inter-area fuzzy logic based power system stabiliser that uses signals extracted from coherent connected areas is prooved to be quite effective in providing damping to power system oscillations during different operating scenarios and different system disturbances. The results from implementing such a scheme in a two-area system are encouraging and promot the implementation of the proposed stability enhancment technique in large multi-area systems. This is demonstrated in the follwing chapter (Chapter 7).

6.4.1.3. Evaluation of transfer capability improvement by GFPSS

As shown in the previous discussion section, adding the global control loop to the existing local control loop in the two area system enhanced the damping capabilities for inter-area oscillations in the system. To evaluate the performance of the developed controller and to show its effectiveness in improving system transfer capabilities, its performance under increased load demand was studied in this section. The base case study (original case study) was set in such a way that area A1 was exporting 413MW to area A2 across the interconnection between them. In these operating conditions the system was damped when subjected to changes in its operating conditions as shown in figure (6-10) (the system was operating with no PSSs). The system was, however, stabilised by implementing different types of PSSs including the developed GFPSS. To study the impact of the developed GFPSS on the control performance, different load increment scenarios were applied.

A. *Increase of 200MW load in area A2.*

This increase in load demand in area A2 led to an increase in the power transfer between area A1 and area A2 from 413 to 531MW as shown in figure (6-19); this corresponds to 28.8% increase in power transfer between the two areas. Figure (6-19) shows the system response with and without the developed GFPSS. It can be seen that the system performance with only local PSS in service became more oscillatory as power transfer across the tie-line is increased. With GFPSS included in the control scheme, the system had only one cycle of oscillation after which it regained a stable equilibrium.

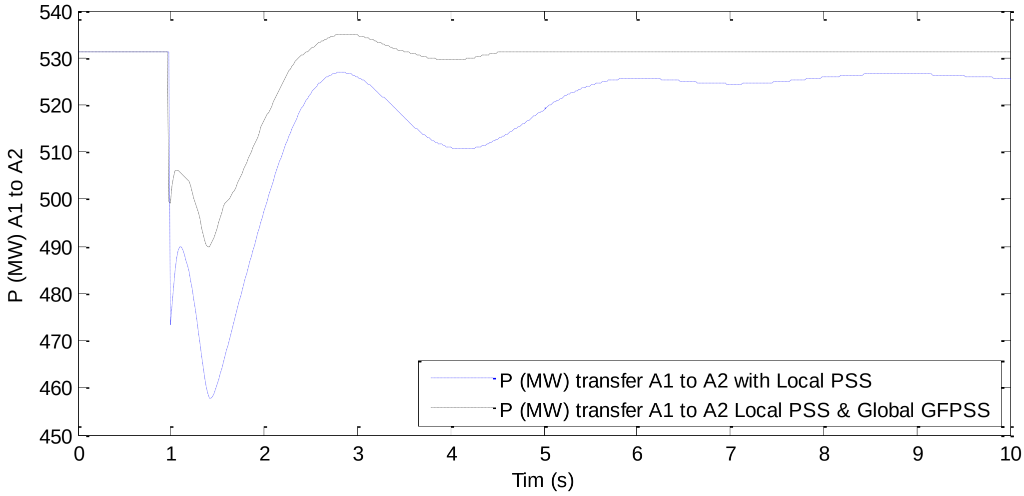

Figure 6-19: System response with increase of 28.8 % power transfer from A1 to A2

B. *Increase of 300MW load in area A2*

In this operating scenario, the load in area A2 was increased by 300 MW compared to the original study case. This increase in load demand in area A2 caused the power transfer across the tie-line to increase by an extra 163MW (i.e. transfer between A1 and A2 became 576 MW as shown in figure (6-20), (base case was 413MW)). This corresponds to a 39.5% increase in power transfer from A1 to A2. Figure (6-20) shows the system response with and without the GFPSS with clear superiority in the performance of the system when the GFPSS was implemented. The superiority in the performance is shown it terms of damping capabilities (less oscillations with GFPSS) and speed of recovery (the system regained its pre-fault equilibrium more quickly with GFPSS)

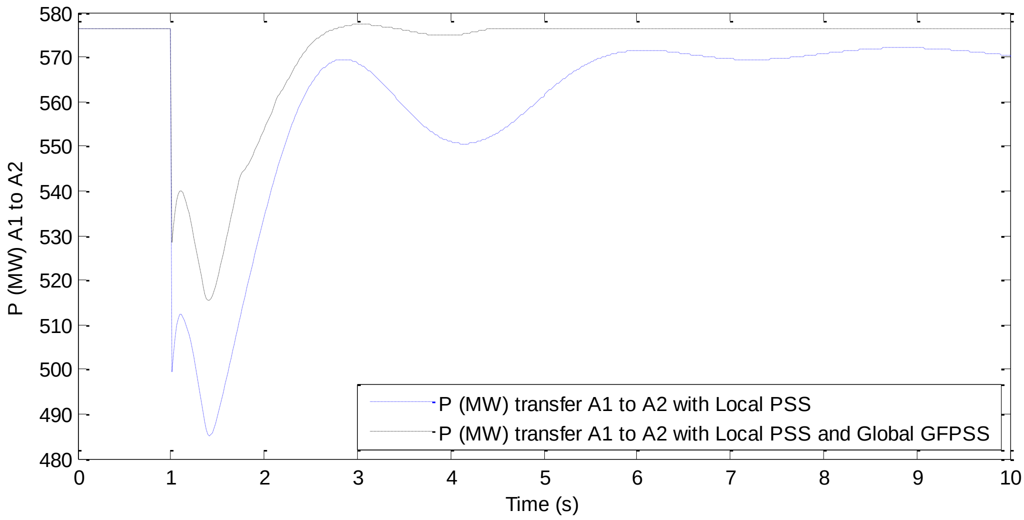

Figure 6-20: System response with increase of 39.5 % power transfer from A1 to A2

C. *Increase of 500 MW load in area A2*

This increase in load demand in area A2 led to an extra 234 MW being transferred from area A1 to area A2. As shown in figure (6-21), there was 646 MW power transfer from area A1 to area A2 in this case which corresponds to a 56% increase in power transfer compared to the base case. With the addition of the GFPSS control loop, the system stability was maintained more effectively compared the local PSS loop. The performance of the local PSS became more oscillatory whereas with both local PSS and GFPSS in service, the damping of the oscillations was enhanced.

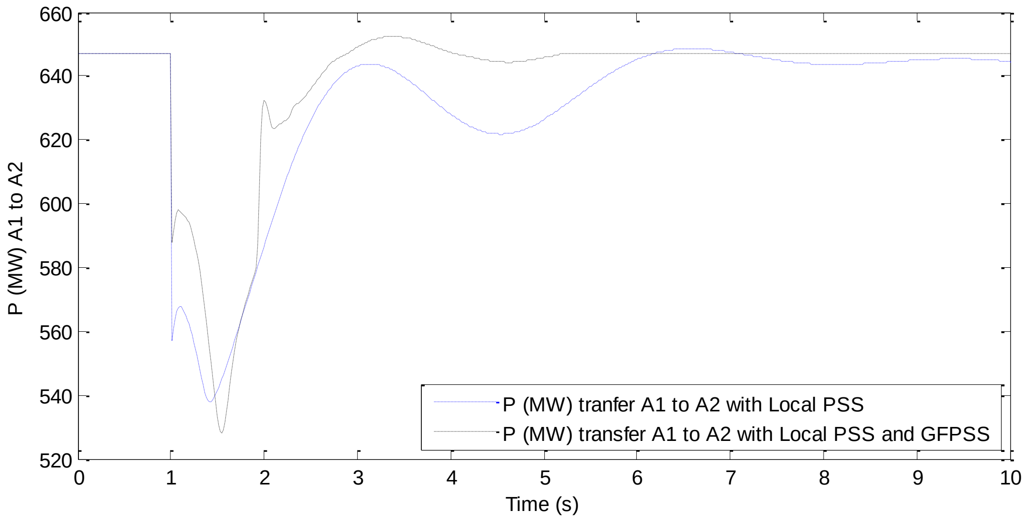

Figure 6-21: System response with increase of 56 % power transfer from A1 to A2

D. *Increase of 600 MW load in area A2*

This increase in load demand in area A2 led to an increase of power transfer between the two areas by 257 MW. From figure (6-22), the power transfer from area A1 to area A2 was 670 MW which correspond to a 62% increase in power transfer compared to the 413 MW in the base case. It can be seen from figure (6-22) that there was a growing oscillations as power transfer across the interconnection was increased. Even with inclusion of the GFPSS in this case, the oscillation magnitude and duration were higher than the previous scenarios. Operating scenarios, where oscillations were not damped quickly, were not acceptable for system security.

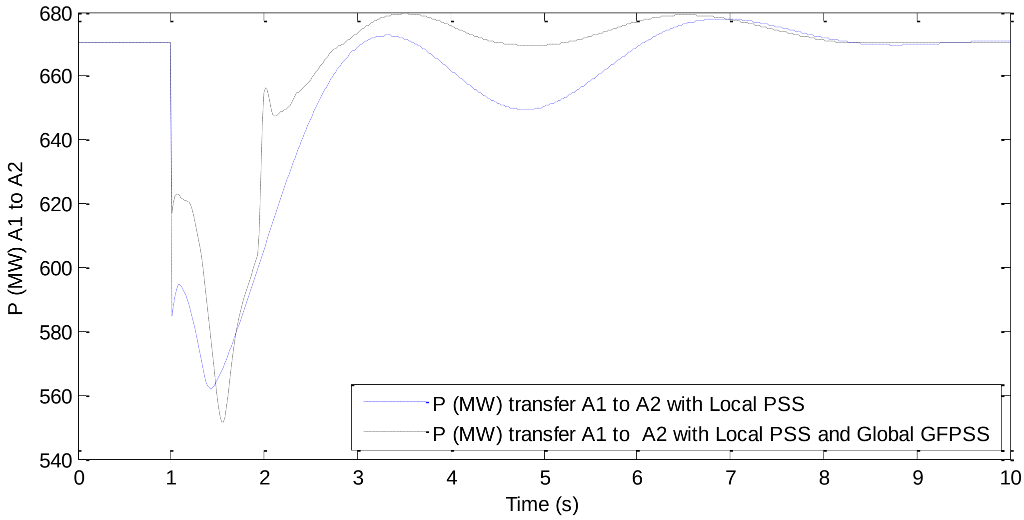

Figure 6-22: System response with increase of 62 % power transfer from A1 to A2

Figure (6-23) shows the response of the system for increment of 200 MW and 600 MW in load in area A2. Those two cases correspond to the 28.8% (531 MW) and 62% (670 MW) increases in power transfer across the tie-line above the base case (413 MW).

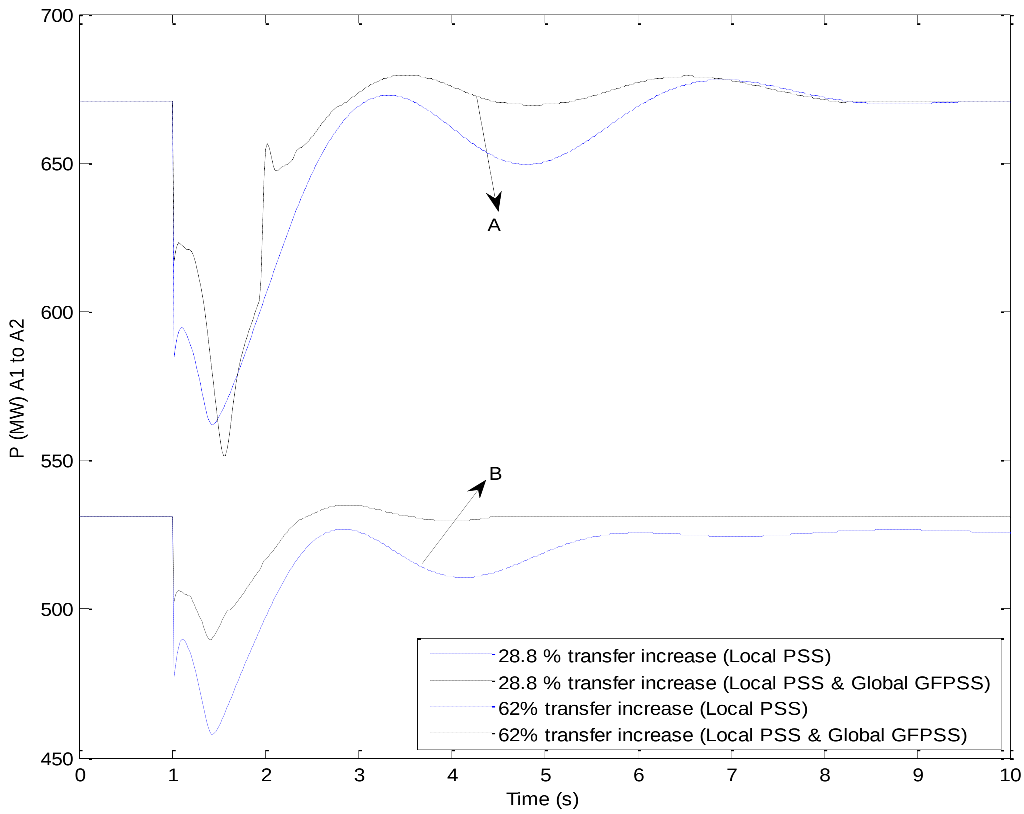

Figure 6-23: System response during 28.8 % and 62 % increase in power transfer

It can be seen from figure (6-23) that the system damping response, when there was a 62% increase in power transfer and a GFPSS was in service, is quite close to that when there was a 28.8% increase in power transfer and only Local PSS was in service (labelled A and B respectively in the graph) . The similarity can be shown in terms of the number of oscillations and their duration. This implied that the system dynamic performance with 62% power transfer increase and GFPSS in place was as good as that with 28.8% increase and only Local PSS was in operation. The increase in power transfer between the two cases is 26.2%, ({[(670-531)/531]*100%}). As a result it can be concluded that the inclusion of the global GFPSS control loop enhanced the transfer capability of the two area system by 26.2%.

6.5. Summary

A new wide-area based control scheme in the form of a Global Fuzzy Logic Power System Stabiliser GFPSS is introduced in this chapter. The proposed stabiliser is designed using fuzzy logic control design approach. The outcome is a fuzzy logic controller which is basically a rule-based control algorithm that utilises the principle of fuzzy set theory in its data representation and its logic. To this, the fuzzy logic theory and its application in power systems is introduced in some details with emphasis on the application of fuzzy logic as power system stabilisers in power system stability control enhancement schemes. The design procedures of fuzzy logic based power system stabilisers FPSS in terms of selection of control variables, fuzzification techniques, of membership function definition, rule-base and inference techniques and de-fuzzification strategy is discussed in details. Also, proposed methods and strategies to enhance the performance of fuzzy logic based power system stabilisers are summarised to identify areas for further improvements to their performance.

The proposed scheme involves adding a global control loop to include a wide-area fuzzy logic based power system stabiliser (GFPSS). This global control loop form a second level of supplementary control in addition to the typical local control loops where typical local power system stabilisers (PSSs) are implemented. The structure and architecture of the proposed control scheme is described in details. The technique by which the wide-area control signals are extracted from data acquired from pre-identified coherent connected areas is illustrated. These wide-area control signals are taken as feedback signals to establish the input control signals to the proposed GFPSS controller. The produced control signals by the proposed GFPSS is added to local stabilising signals produced by the local PSSs to provide the required wide-area based control signals that allow system's generators to have a wider view of the power system. The additional global control signal allows the entire control scheme to act based on a system wide view rather than acting based on local area information. Initially, the proposed controller is implemented for a two-area based power system for ease of design and demonstration. The two-area four-machine Kundur test system is used to demonstrate the implementation of the proposed design. The performance of the GFPSS is tested under a range of operating scenarios and for both small disturbances and large disturbances. Results show that the addition of the wide-area based control signal provided by the proposed controller has the potential to play a significant role in enhancing power system stability due to its effectivness in providing adequate damping to power system oscillations during different operating scenarios and different system disturbances. The developed control scheme is shown to have enhanced the transfer capability of the system by a margin of 26.2 % which is quite encouraging. The scheme is generalised in the next chapter (Chapter 7) to be implemented in multi-area large power systems.

Chapter 7: Implementation of the Designed Controller in Multi-area Power Systems

As mentioned in the chapter 6, the proposed stability enhancement scheme is designed to implement a GFPSS that act upon wide-area signals acquired from remote places within the power system. The wide-area remote signals are extracted from pre-defined coherent connected areas as shown previously in equations (6.9) to (6.11). In a multi-machine, multi-area power system environment and for the scheme to be effectively implemented, coherent areas within the power system have to be identified prior to implementation. For each two coherent, yet connected, areas or clusters of synchronous generators a GFPSS could be implemented. Hence the techniques described in chapter 4 and [50] to determine the coherent clusters in a multi-machine power system are for a significant use in implementing the proposed scheme. Also determining the critical clusters and the significance of the tie-lines connecting these clusters is very important in choosing which tie-lines to use to provide the proper input control signals to the GFPSS. The techniques described in chapter 5 and reference [90] are used here to identify those critical lines and clusters to fully implement the proposed GFPSS. In this chapter the control scheme architecture is generalised such that the control scheme can be implemented in a multi-area power system

Figure (7-1) shows the general structure of the proposed scheme which enables implementation of the GFPSS in a multi-area power system. For a system where a number of coherent areas or clusters are identified, a GFPSS can be implemented to act between each two connected areas. The two coherent clusters have to be connected so the deviation in the active power of the tie-line (ΔP_{tie}) connecting these two areas is used as an input control signal to the GFPSS.

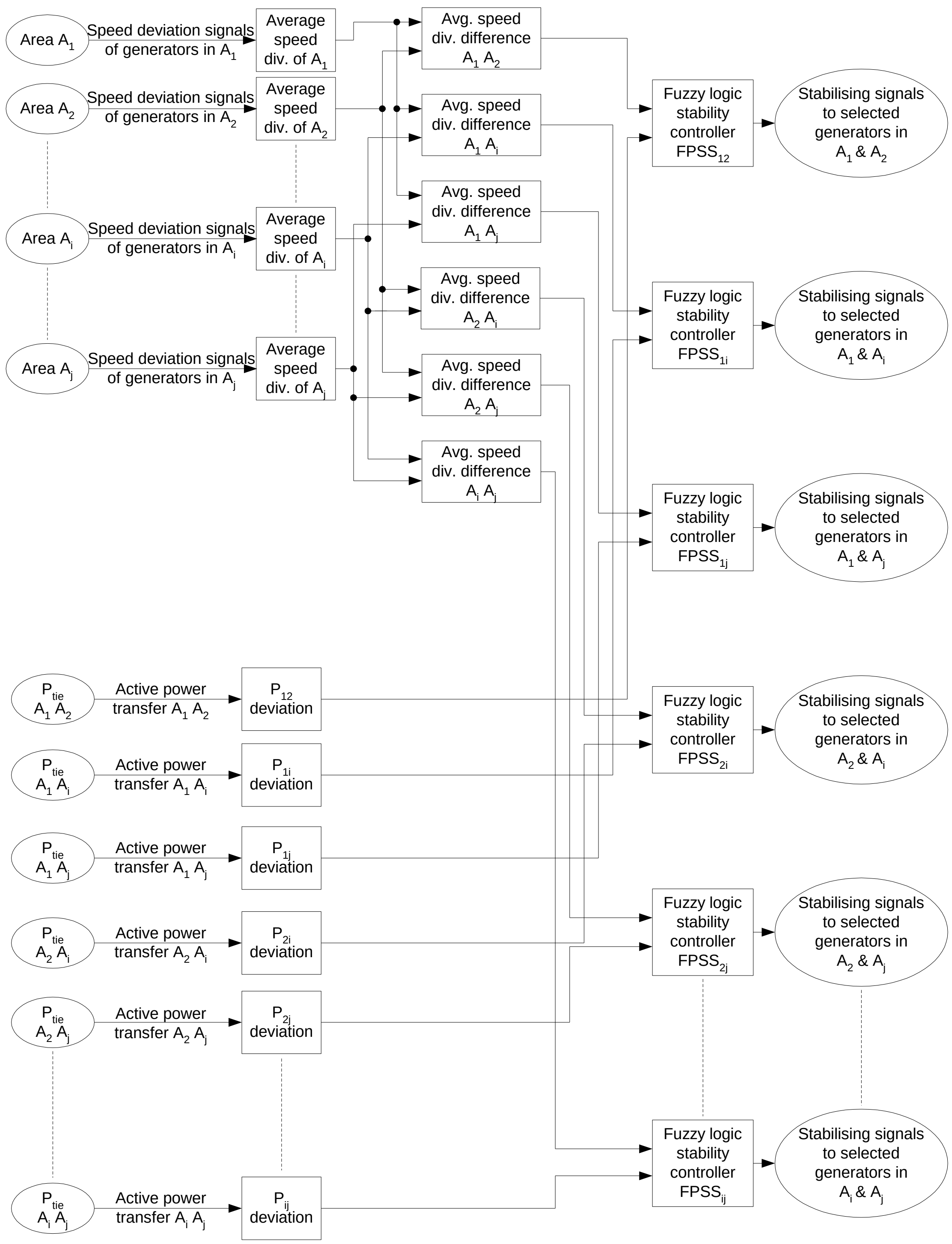

Figure 7-1: General structure of inter-area GFPSS

For each two coherent areas, the difference in the average speed deviation between the two areas $\overline{\Delta\dot{\omega}_{ij}}$ is calculated as in equations (6.9) and (6.10). This forms the first input control signal to the stabiliser implemented between those two areas $GFPSS_{ij}$. For each two coherent areas, a tie-line connecting them is identified from which a second input control signal, namely the deviation in the tie-line active power $(\Delta P_{tie})_{ij}$, is extracted and fed into the $GFPSS_{ij}$. The deviation in the tie-line active power between any two connected areas is calculated as in equation (6.11). This process is illustrated in details in figure (7-1) above. The proposed scheme is implemented in two test systems which mimic real world power systems. The coherent areas for both systems are pre-defined[4]; the 16 generator 5 areas test system and the IEEE 10 generators 39-bus test system (two areas).

7.1. Case Study 1: 16-Generator 5-Area Test System

The 16-generator test system is used to evaluate the clustering algorithm introduced in chapter 4. In this system, there are 68 buses and 16 generation units, interconnected via high voltage transmission lines. The system is highly recommended in the study of inter-area oscillations in power systems and in finding coherency property between synchronous generators in multi-machine interconnected power systems. In chapter 4, five coherent areas were identified when applying the clustering algorithm to the system as shown in figure (7-2). In chapter 5, these coherent areas are evaluated in terms of their criticality to the system stability. The techniques introduced in chapter 5 give insight and information about these areas and allow determination of key areas and interconnections for which enhanced control schemes can be implemented. Referring to the analysis introduced in chapter 4 and 5, cluster 1, consists from generators G1 to G9, is a cluster of a significant interest for possible implementation of the stability enhancement control scheme introduced above, the GFPSS. Analysis of the system in chapter 5 shows cluster1 to be oscillating against the other clusters most of the time during different system disturbances. These observations are taken as the bases in implementing the proposed GFPSS into this multi-area test system. The system is modelled using the dynamic simulation programme DIgSILENT (*Digital Simulator for Electric Network*). All generation units are equipped with excitation systems and speed governors control. Generators G1, G2, G4, G6, G7 and G9 in cluster 1 are equipped with conventional power system stabilisers which represent the local control loop LPSS. Generators G10 and G12 in cluster 2 are equipped with similar LPSS. Therefore, the signals from the implemented GFPSS are directed to those generating units with local stabilising control loop LPSS.

[4] See chapters 4 and 5.

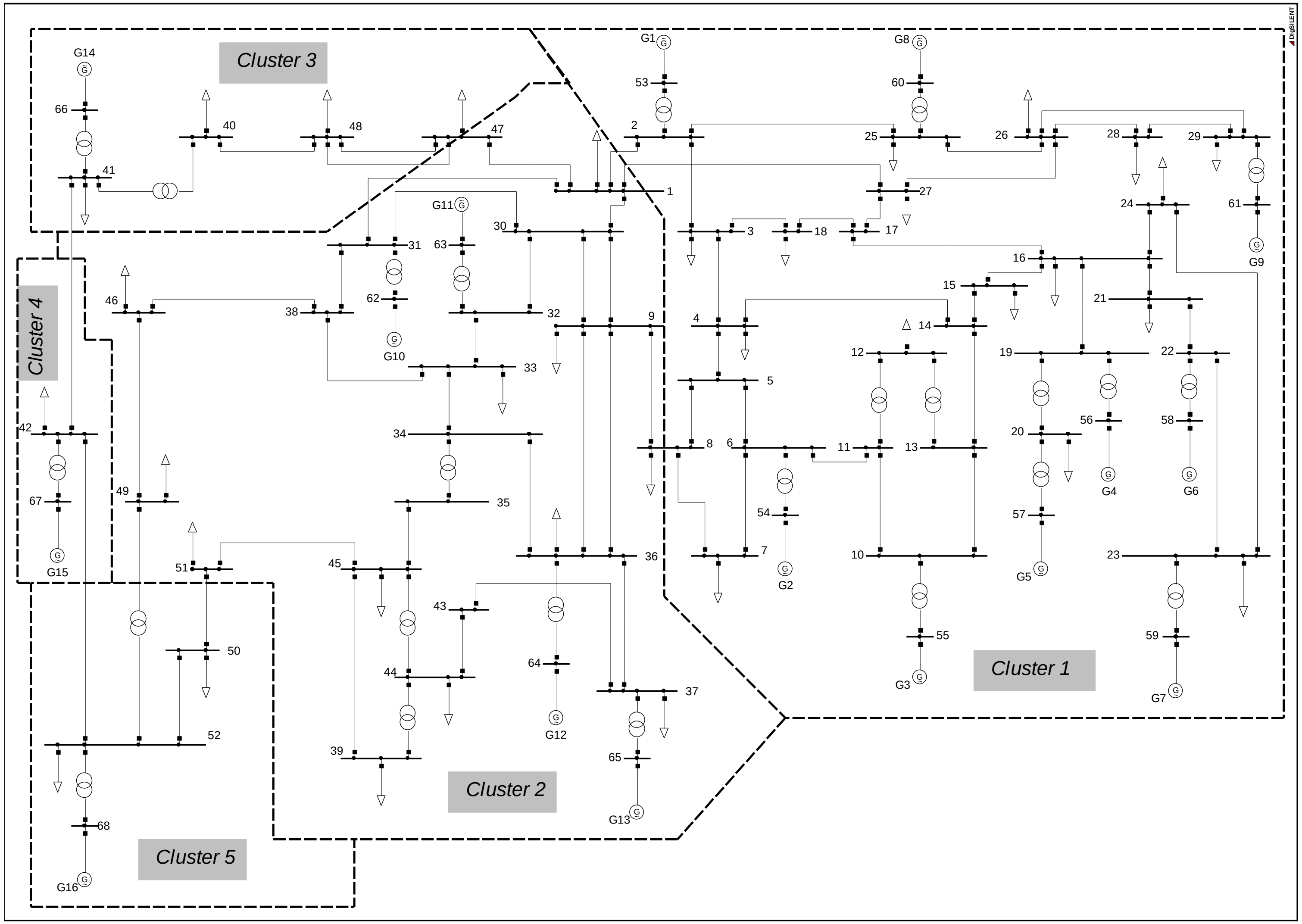

Figure 7-2: 16-generator 5 clusters test system

In theory, a GFPSS can be implemented between any two coherent connected clusters as the developed structure shown in figure (6-19) illustrates. However, in this simulation exercise, the focus is put on those units with local PSS as the global additional signal is added to the local signal as illustrated in figure (6-7) in (chapter 6). Different disturbances, small and large, are considered. The performance of the system is evaluated using time domain simulation from which the response of the system to different operating scenarios is observed and evaluated.

A. *Performance during small disturbances*

For small signal disturbance, a number of scenarios are considered as to allow for robust testing to the control scheme. The first scenario is applying a pulse of 5% magnitude at the voltage reference of generator G9 located in cluster 1 for a time period of 50 ms. During this time, the system's response to this disturbance is monitored under a variety of available control strategies. Figure (7-3) shows the active power transfer measurement across line 8-9 connecting cluster 1 and 2. The active power transfer across the mentioned line without a GFPSS is plotted against that when a GFPSS is implemented in different locations within the network. Notice that the GFPSS signals are dispatched only to those generators equipped with LPSS as explained above.

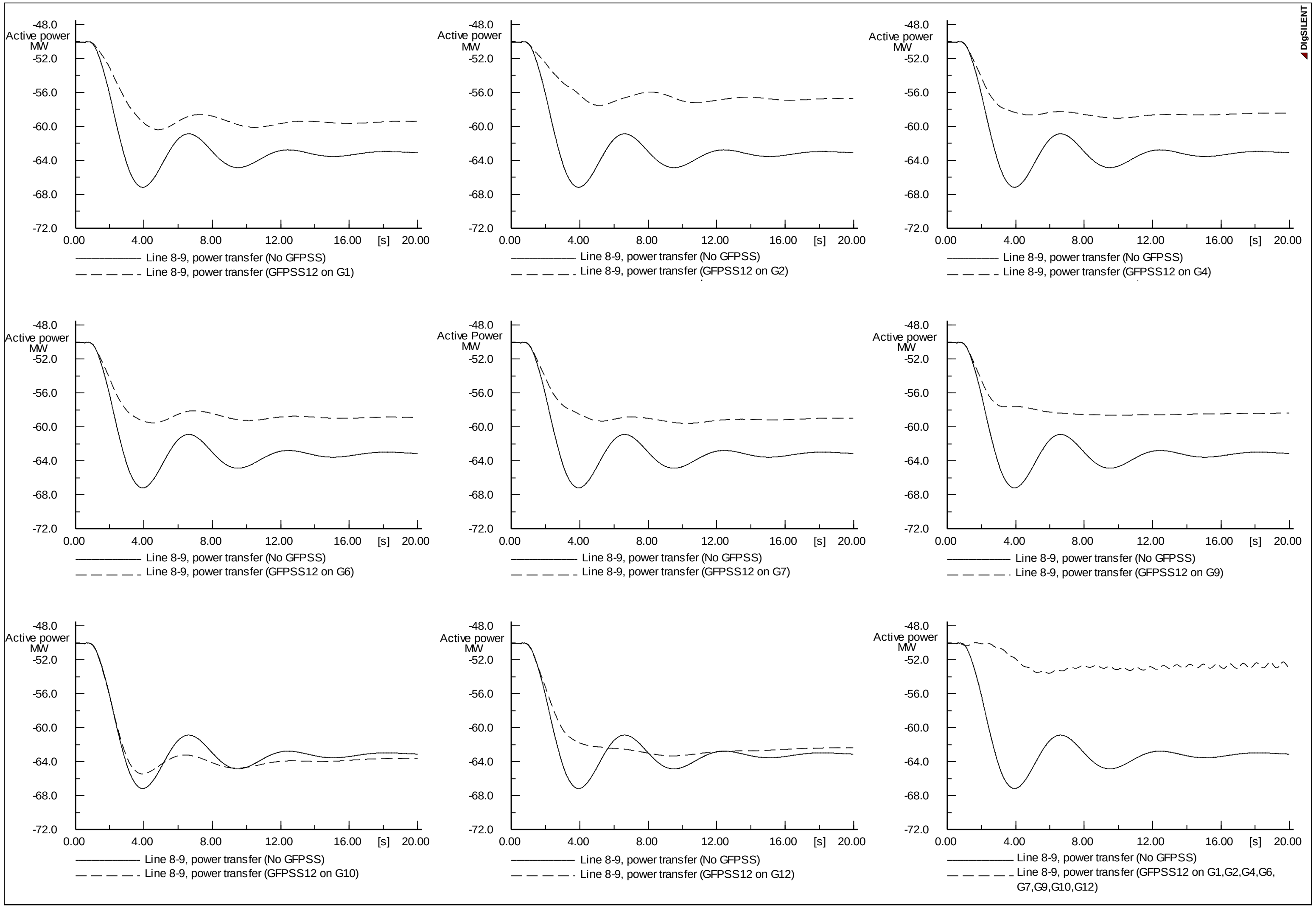

Figure 7-3: Line 8-9, active power transfer with and without GFPSS scheme

For example, the top left graph in figure (7-3) is a plot of active power measurements across line 8-9, the bold line shows the signal when only LPSS is in service whereas the dotted line shows the signal when implementing the additional GFPSS, which provides the remote wide-area based signal, and adding it to the local signal from the LPSS. The GFPSS in this case is allocated at generator G1 in cluster 1. A significant improvement of the system's response to the disturbance is clearly shown. The oscillations in the active power across the monitored transmission line seem to be damped more effectively when adding the GFPSS loop into the control scheme. Not only the duration of the oscillations is significantly reduced, but also their magnitude is noticeably enhanced (decreased). Similar observations are clearly shown when dispatching the GFPSS to other generators within the clusters. Although the response is slightly different from one case to another, yet the overall system performance is enhanced in all cases. The graph in the bottom right of figure (7-3) shows the system's response when adding the remote control signal from the GFPSS to all the considered generators in the system (i.e. G1, G2, G4, G6, G7, G9, G10 and G12). Dispatching the remote control signal to all the generators seem to have a negative impact on the overall control performance, which indicates that it might be a good practice is to allocate the remote control signal to a fewer number of generators and not all of them at once (for example 3 or 4 generators would be sufficient in such system in case one of the remote signals fail to reach one generator so the others could pick it up, hence, provide some sort of back up scheme). This effect of enhancing the damping capabilities of the system can be observed in other signals such those shown in figure (7-4).

Figure (7-4) shows the difference in the weighted average speed deviation signals between cluster 1 and cluster 2, calculated as in equations (6.9) and (6.10). The implemented control schemes are the same as those considered in figure (7-3). The observations of this figure support those explained above with regard to the enhanced damping capabilities of the system when implementing the additional GFPSS control loop to the selected generators. It also shows that a negative impact might occur when including all the considered generators into the control scheme.

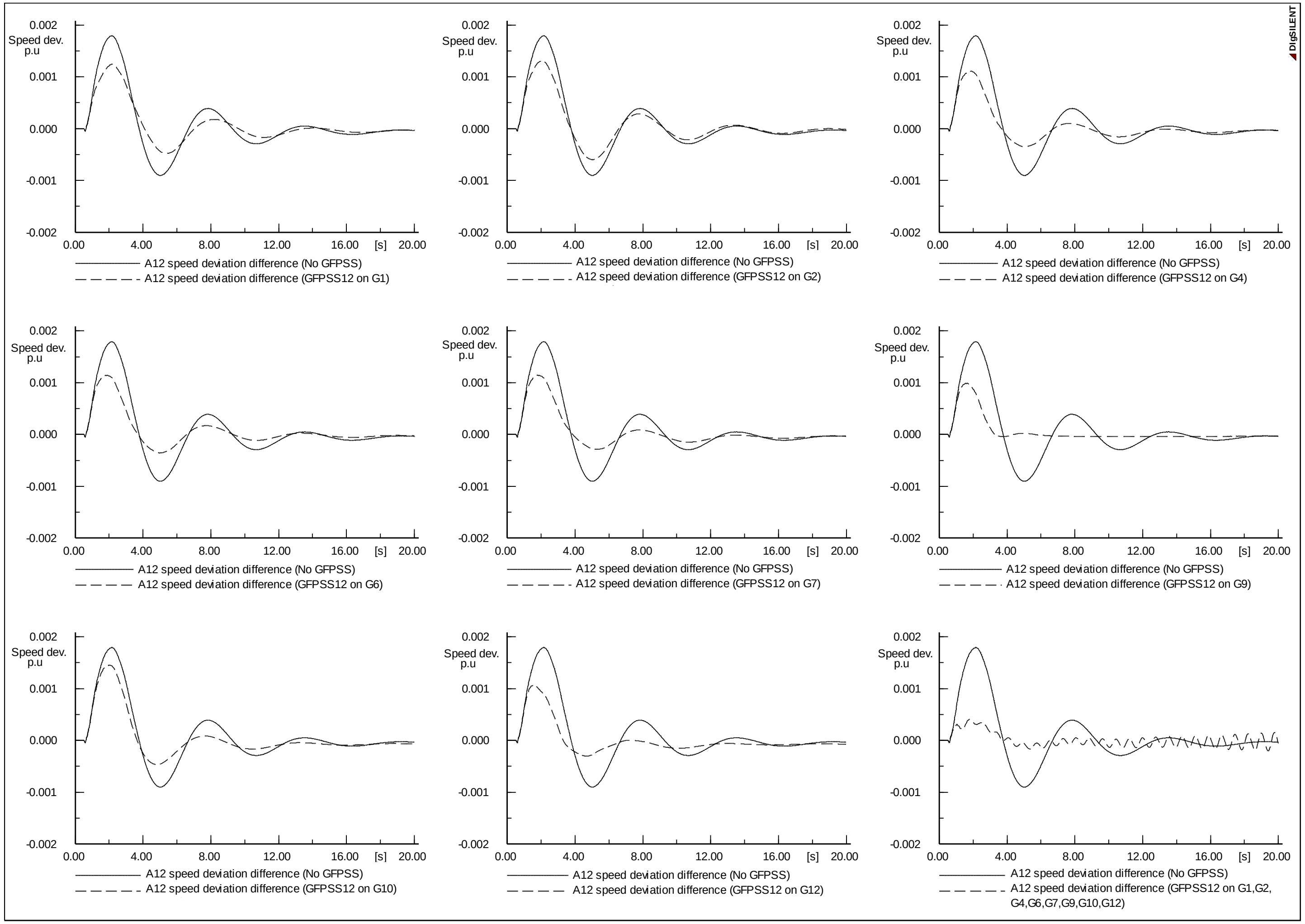

Figure 7-4: Speed deviation difference between cluster 1 and 2 with and without GFPSS scheme

To evaluate how such improvement in the system response to the disturbance is achieved, figures (7-5) and (7-6) show some of the individual generators' responses to the disturbance when implementing the GFPSS loop at generator G1 in cluster 1.

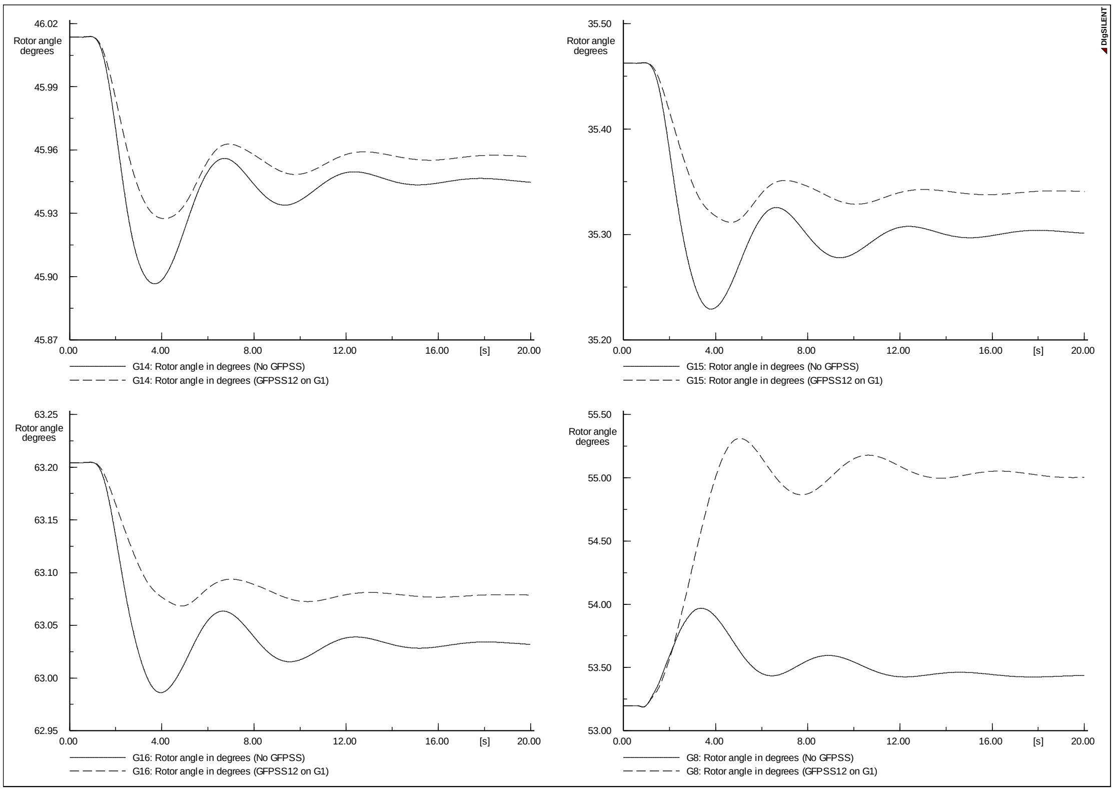

Figure 7-5: Generators' rotor angle in degrees (with and without GFPSS scheme)

Figure (7-5) shows the rotor angle response of generators G14 in cluster 3, G15 in cluster 5, G16 in cluster 4 and G8 in cluster 1 to the disturbance. The response of G14, G15 and G16 is better when implementing the GFPSS loop in G1. The oscillations in their rotor angle are enhanced both in duration and magnitude. However, G8 seems to have different response as its rotor angle increases dramatically, yet, regain a stable equilibrium in an acceptable time frame. Figure (7-6) shows the rotor angle response of generators G5, G7, G9 (in cluster 1) and G12 in cluster 2. Again, an enhanced response can be seen in terms of rotor angle oscillation damping to those units with the exception of G9 which seems to have similar response giving both control strategies.

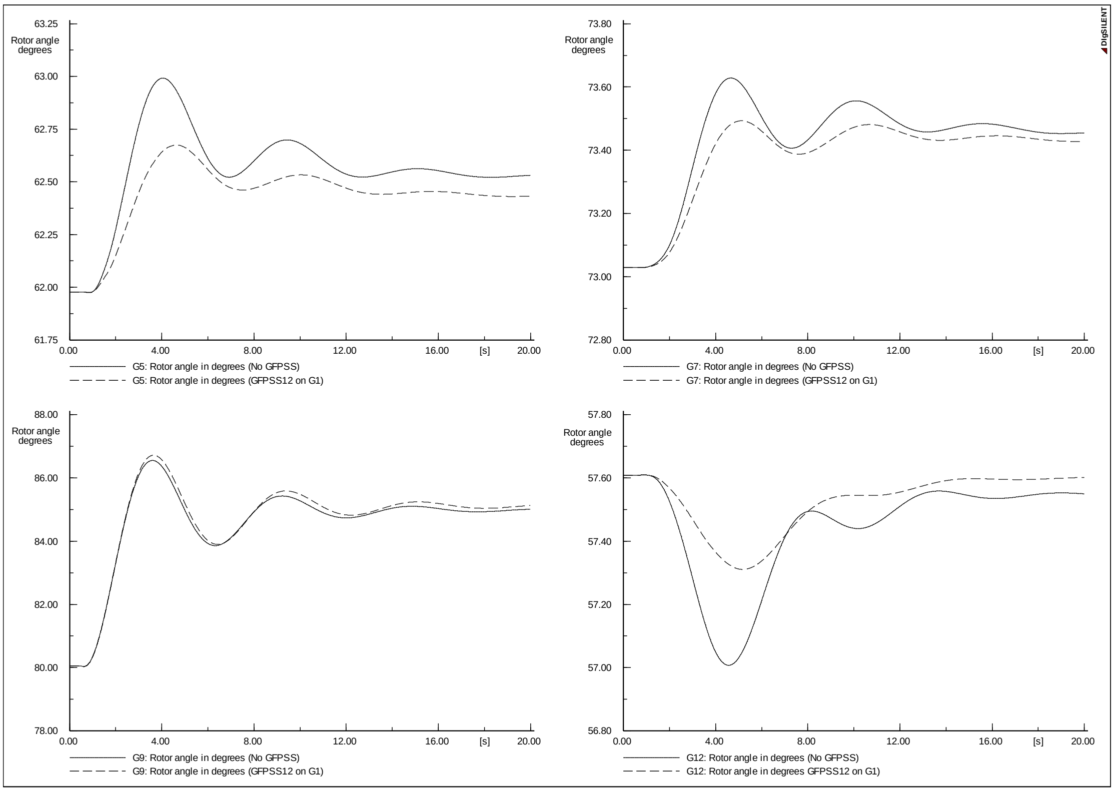

Figure 7-6: Generators' rotor angle in degrees (with and without GFPSS scheme)

The rapid increase in the rotor angle of G8 following the disturbance under consideration seems to have a significant improvement for the overall system performance as power can be transferred across the transmission corridors with significant damping capabilities to the oscillation modes, which results in smoother and fewer oscillations before reaching new stable operation conditions. It seems that the additional control loop of the GFPSS allowed the control system of individual units to have a wider view of the entire system rather than emphasising their control actions locally at the local control level.

The improvement in the overall system performance can be observed all over the network as figures (7-7) and (7-8) illustrate. Figure (7-7) shows the active power transfer across the transmission corridor connecting cluster 2 and 5 (line 50-51, see figure (7-2)). The control scheme is in the same configuration as that explained for figures (7-3). Figure (7-8) on the other hand shows the difference in the weighted average speed deviation signals between cluster 2 and cluster 5.

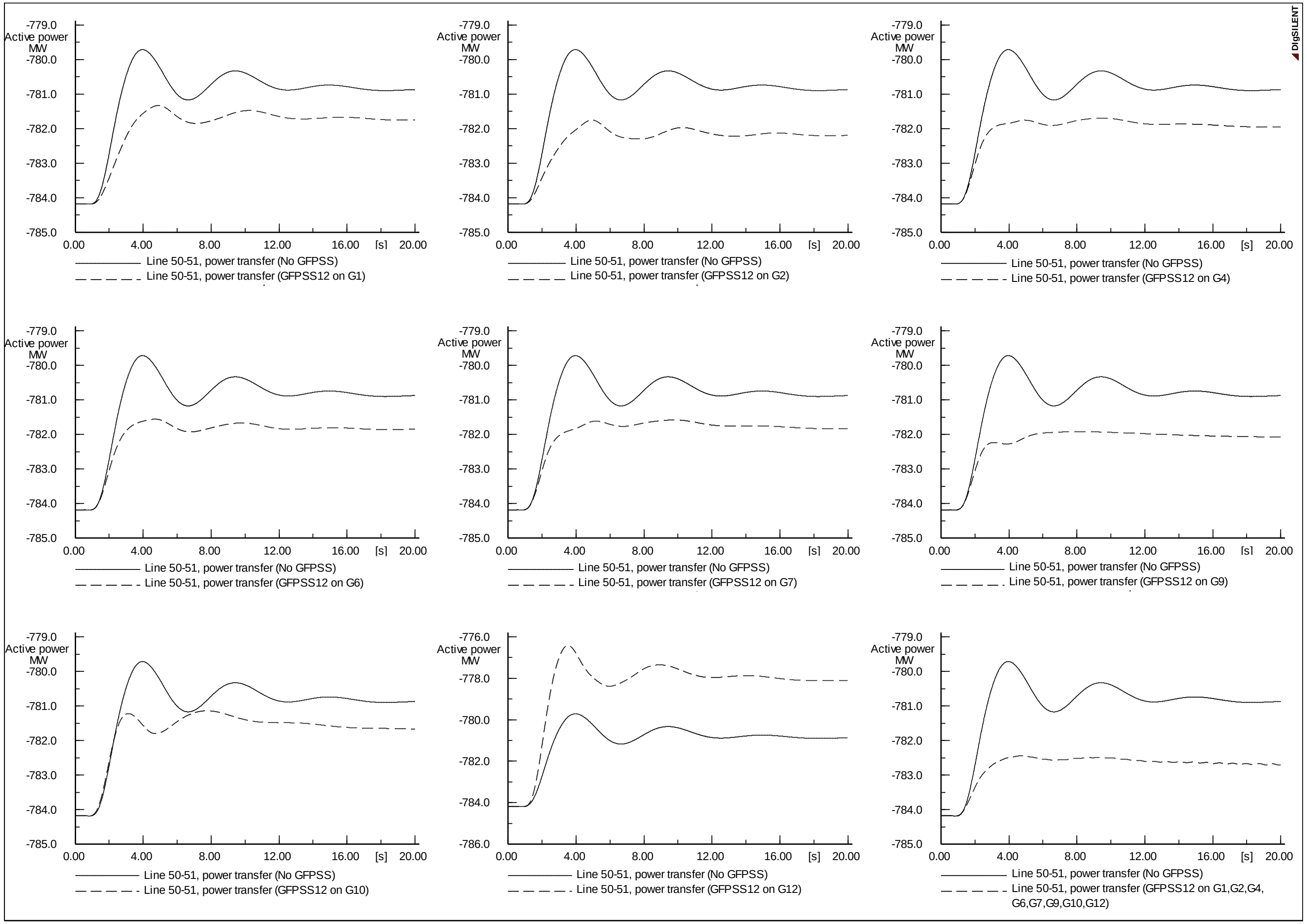

Figure 7-7: Line 50-51, active power transfer with and without GFPSS scheme

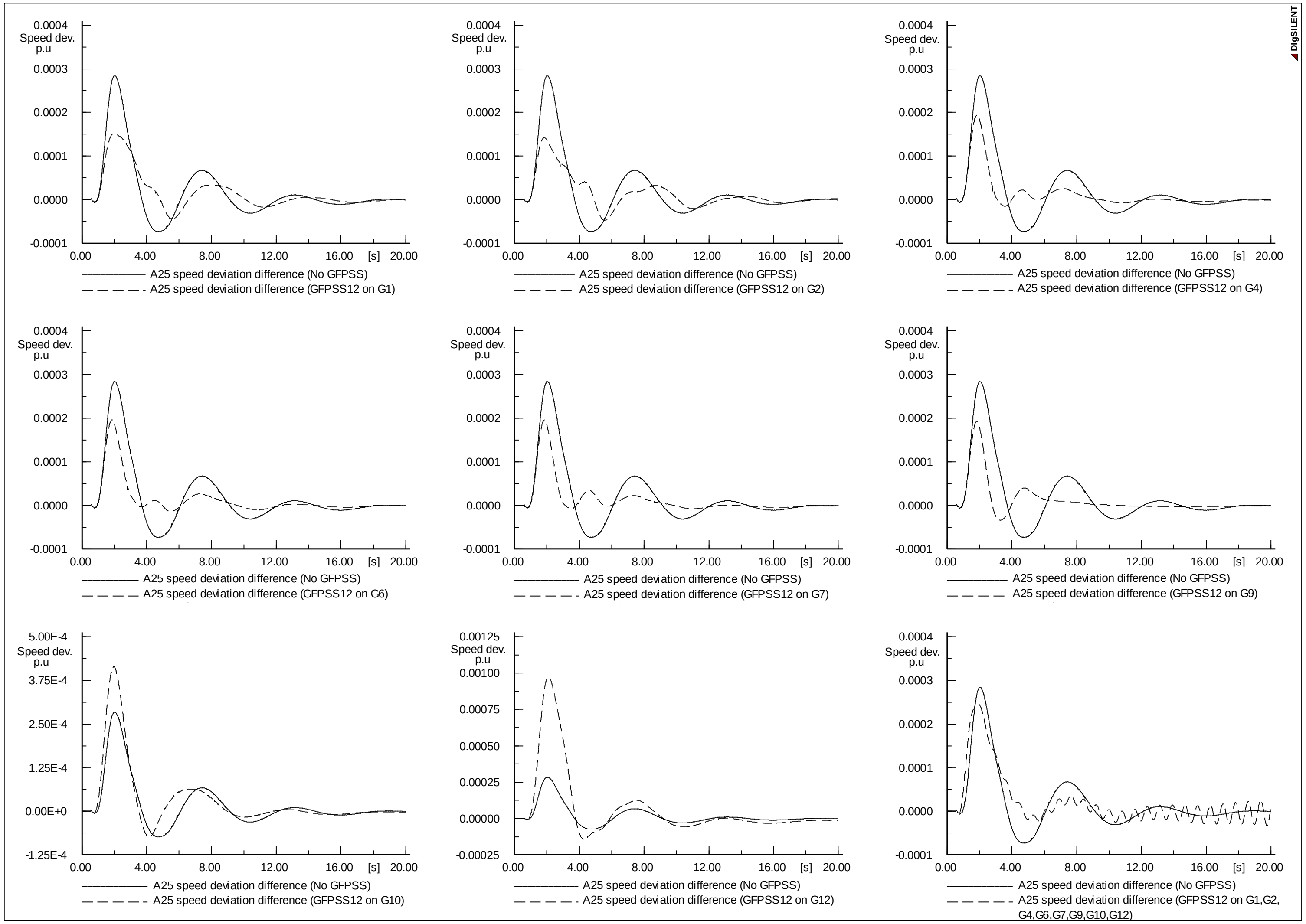

Figure 7-8: Speed deviation difference between cluster 2 and 5 with and without GFPSS scheme

The second scenario is applying a more sever disturbance with comparison to the previous. That is by introducing a pulse of 95% magnitude at the voltage reference of generator G10, located in cluster 2, and for a longer period of time (500 ms rather than 50 ms for the previous case). Figure (7-9) shows the active power transfer measurement across the transmission corridor connecting cluster 1 and 2 (line 8-9). The bold solid lines show the active power transfer across the transmission line without implementing the GFPSS scheme whereas the dotted lines show active power transfer when the GFPSS remote signals are dispatched to the selected generators in the same configurations explained above (i.e. GFPSS signals are allocated to either G1, G2, G4, G6, G7, G9, G10 and G12 or to a combination of those units, which all have a local LPSS control loop).

Figure (7-9) asserts that when adding the GFPSS signals to any of the selected generators, the oscillations in the active power signals are damped more rapidly (fewer oscillations, lower oscillation magnitudes, and smoother transition from pre-disturbance to post-disturbance conditions). It also shows that it is not recommended to use the GFPSS remote signals in all the selected generators at the same time, this is clear in the system response shown in figure (7-9) bottom right. Using the GFPSS signal at all units at the same time would result in oscillatory unstable conditions in the system, a situation that has to be avoided. This will, again, suggest that in order to have satisfactory performance of the GFPSS scheme, it is a good practice to dispatch the GFPSS signal to a pre-selected number of units. It is ideal, for example, to send the remote GFPSS to a one unit in one cluster and to another unit in a neighbouring cluster, hence making sure that at least one remote GFPSS signal is available at one of the units all the time.

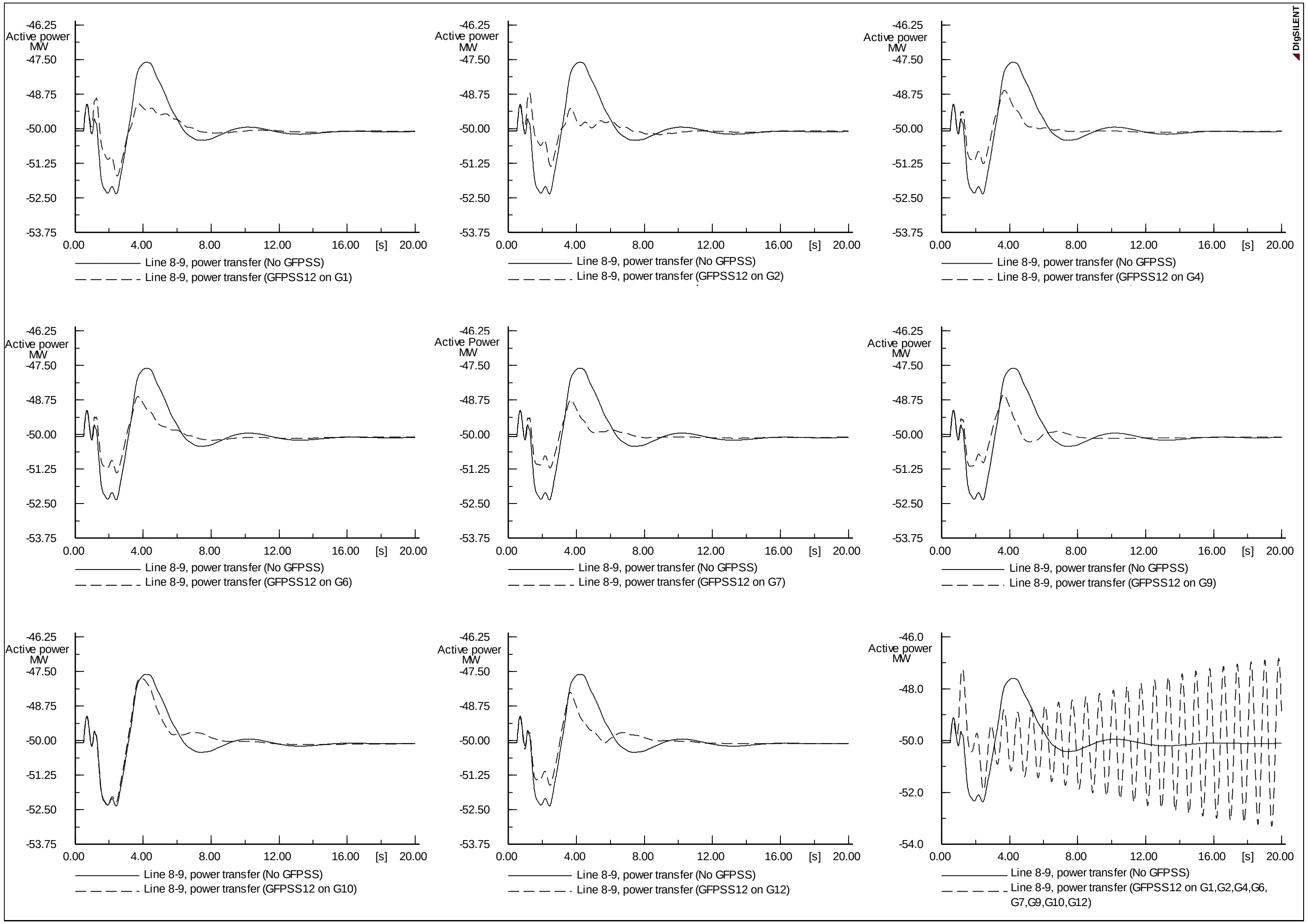

Figure 7-9: Line 8-9, active power transfer with and without GFPSS scheme

Figure (7-10) shows the difference in the weighted average speed deviation signals between cluster 1 and cluster 2, calculated as in equations (6.9) and (6.10). These dynamic signals show how the difference in the weighted speed deviations of cluster 1 and cluster 2 react to the disturbance under the different control schemes. It clarifies the observations made above when monitoring active power transfer between the two clusters. The oscillation damping in the weighted speed deviations differences between the two clusters when implementing the GFPSS is superior to that without the GFPSS. It also clarifies that the use of the GFPSS signals should be limited to a selected numbers of units to avoid deterioration of oscillation damping and occurrence of oscillatory operation conditions in the system.

The response of the individual generators to the considered disturbance is shown by the corresponding trajectories of their rotor angles illustrated in figure (7-11) and (7-12). Both figures show randomly selected generators and their response with and without a GFPSS at G1. Figure (7-11) gives the rotor angles of generators G14, G15, G16 and G2. As can be seen, the performance of those four individual units is enhanced when the GFPSS signal is added to the control scheme of generator G1. The rotor angles of these units seem to oscillate less and regain their post-disturbance status more rapidly.

Figure (7-12) shows rotor angle trajectories of generators G5, G7, G9 and G12. Units G5 and G7 have a better performance when the GFPSS control loop is included in the control scheme of G1. Similarly to the first disturbance discussed above, G9 seem to have a similar response with and without the GFPSS. Unit G12 on the other hand has a slightly higher oscillation magnitude as its corresponding rotor angle increases slightly higher with comparison to the case without a GFPSS, however, its rotor angle does not oscillate dramatically and it attains a stable equilibrium point quite rapidly. As an overall system performance, the inclusion of the GFPSS into the control loops of some of the individual units led to an enhanced overall system performance. The aim is to improve the transmission stability by providing additional damping capabilities to oscillations which would, otherwise, limit power transfer capabilities. The additional wide-area based control signals provided by the GFPSS tend to have this impact when directed to a selected number of generators.

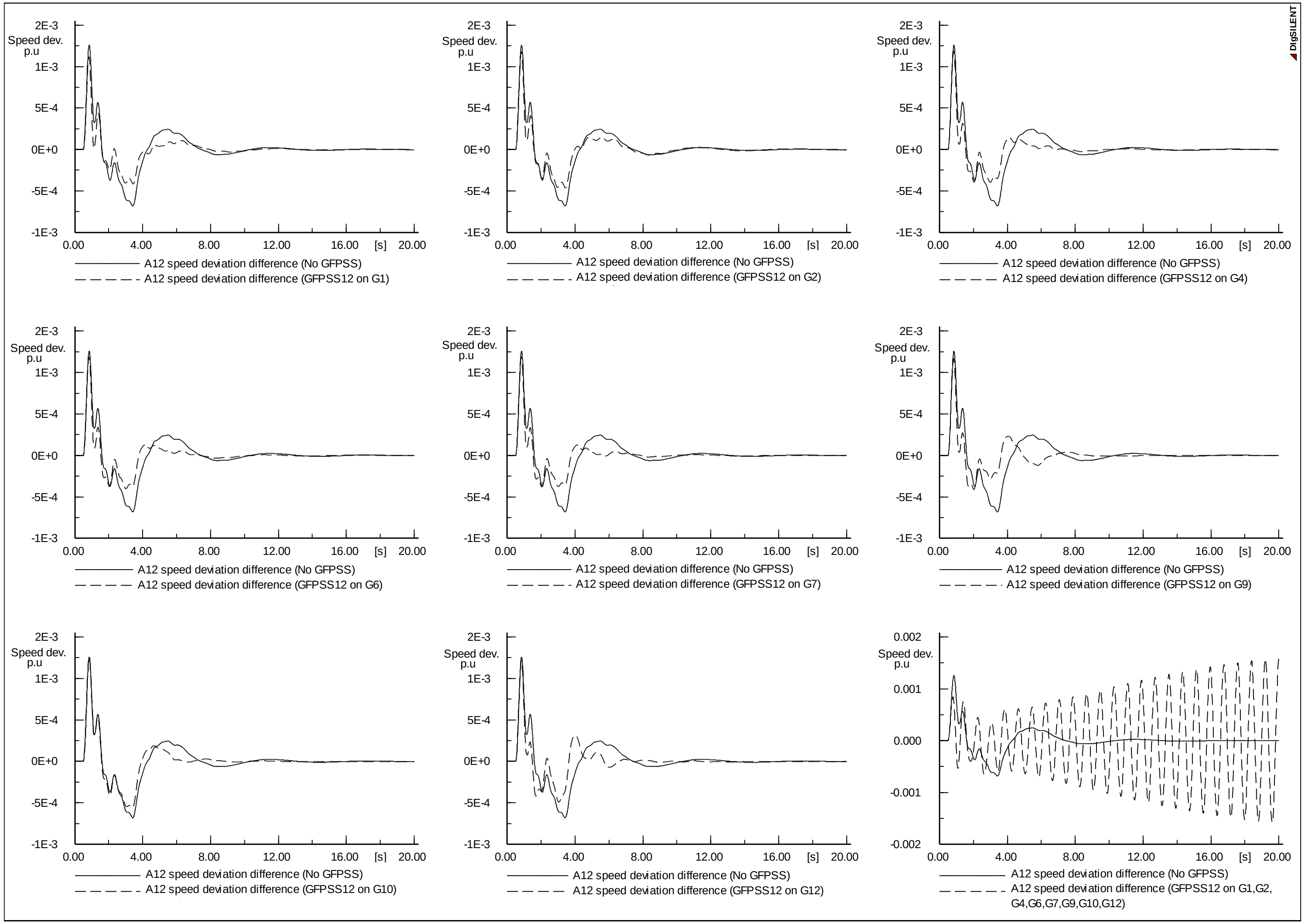

Figure 7-10: Speed deviation difference between cluster 1 and 2 with and without GFPSS scheme

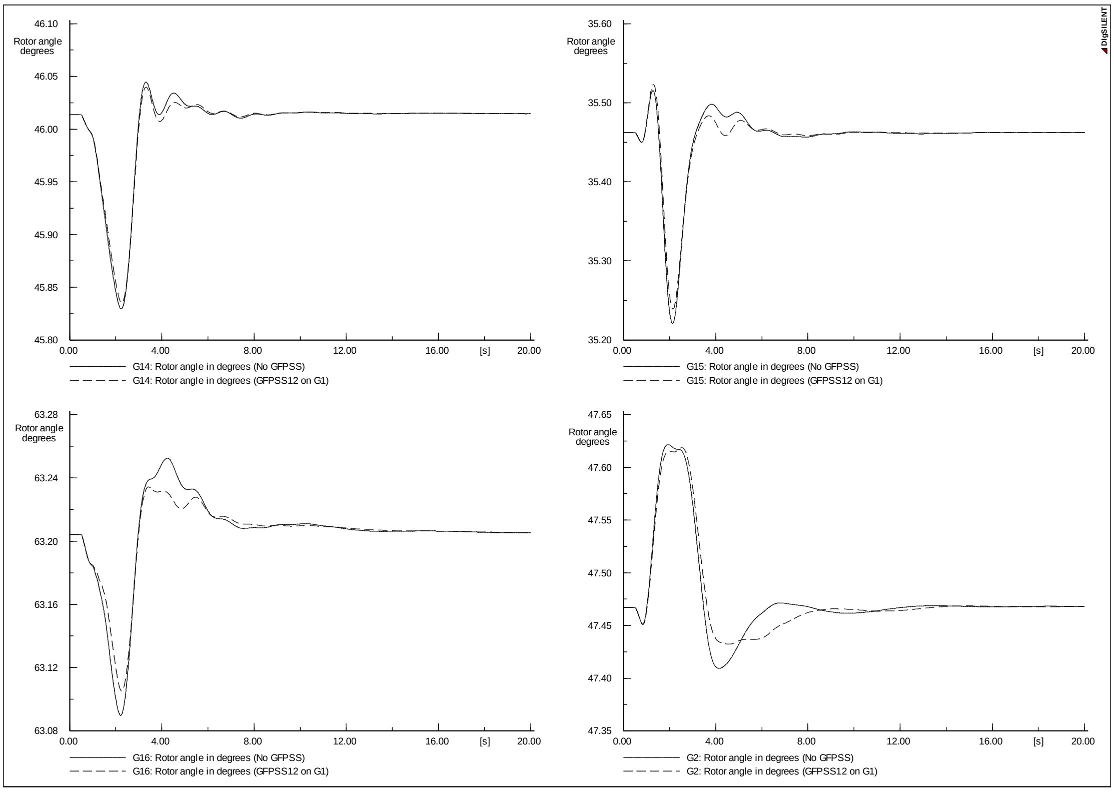

Figure 7-11: Generators' rotor angle in degrees (with and without GFPSS scheme)

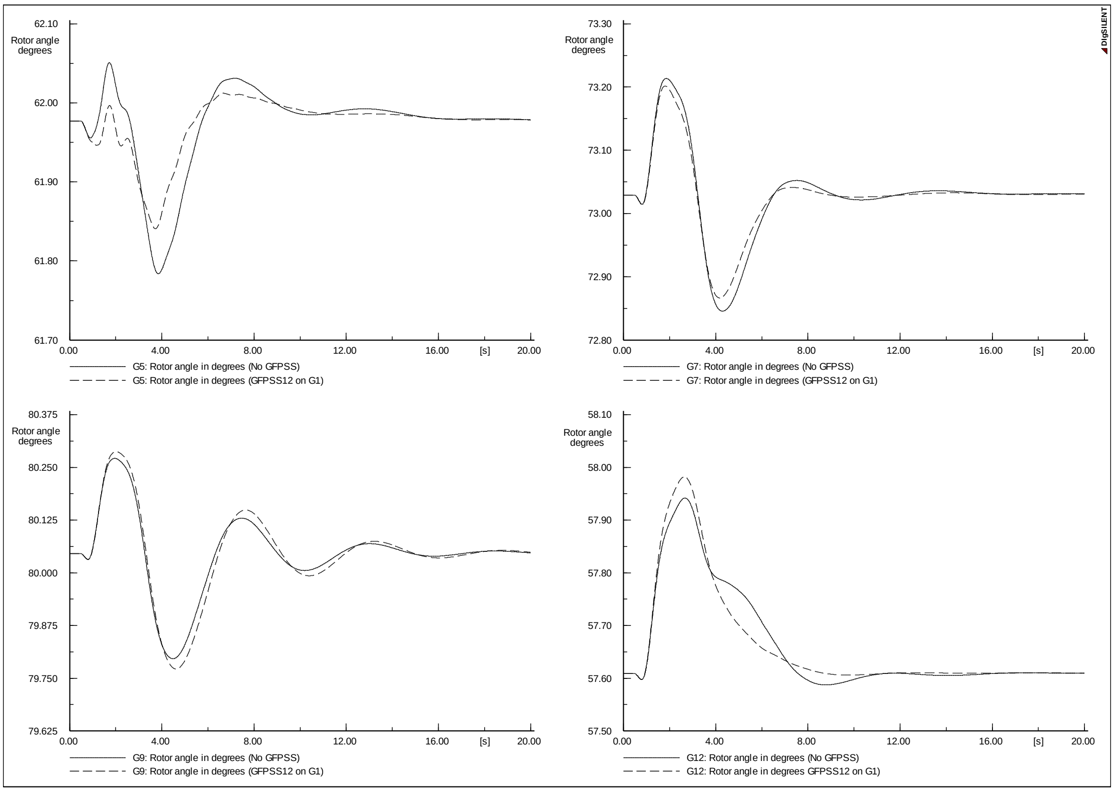

Figure 7-12: Generators' rotor angle in degrees (with and without GFPSS scheme)

Figures (7-13) and (7-14) give support evidence to what has been described as overall system performance. The first, figure (7-13), shows enhanced transfer stability across the transmission corridor connecting cluster 2 and 5 (line 50-51) when using the GFPSS scheme. These results are supported by the second figure; figure (7-14), which shows the difference in the weighted average speed deviation signals between cluster 2 and cluster 5 during the disturbance. Notice the oscillatory unstable response when directing the remote GFPSS signals to all units (bottom right graphs of both figures (7-13) and (7-14)).

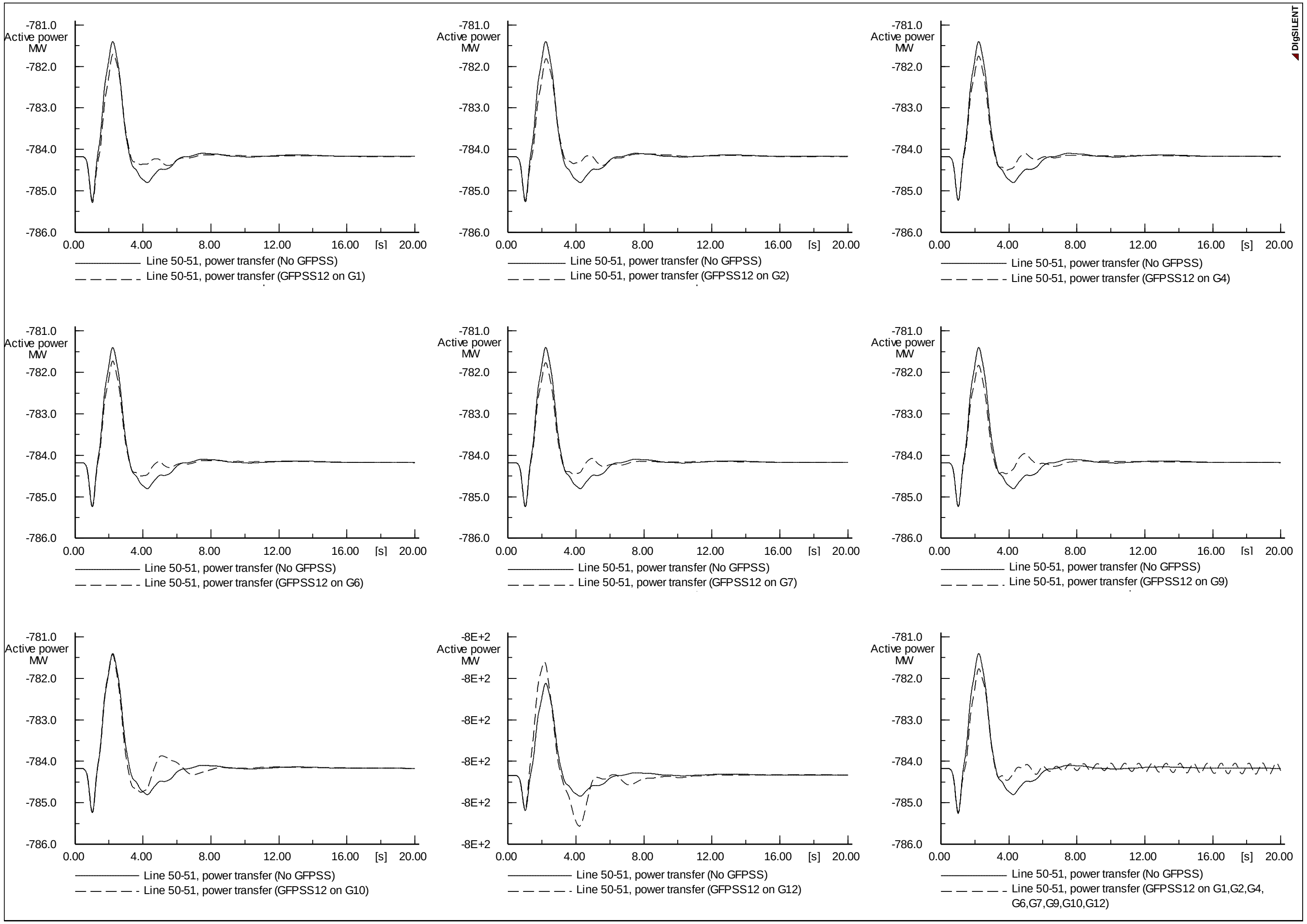

Figure 7-13: Line 50-51, active power transfer with and without GFPSS scheme

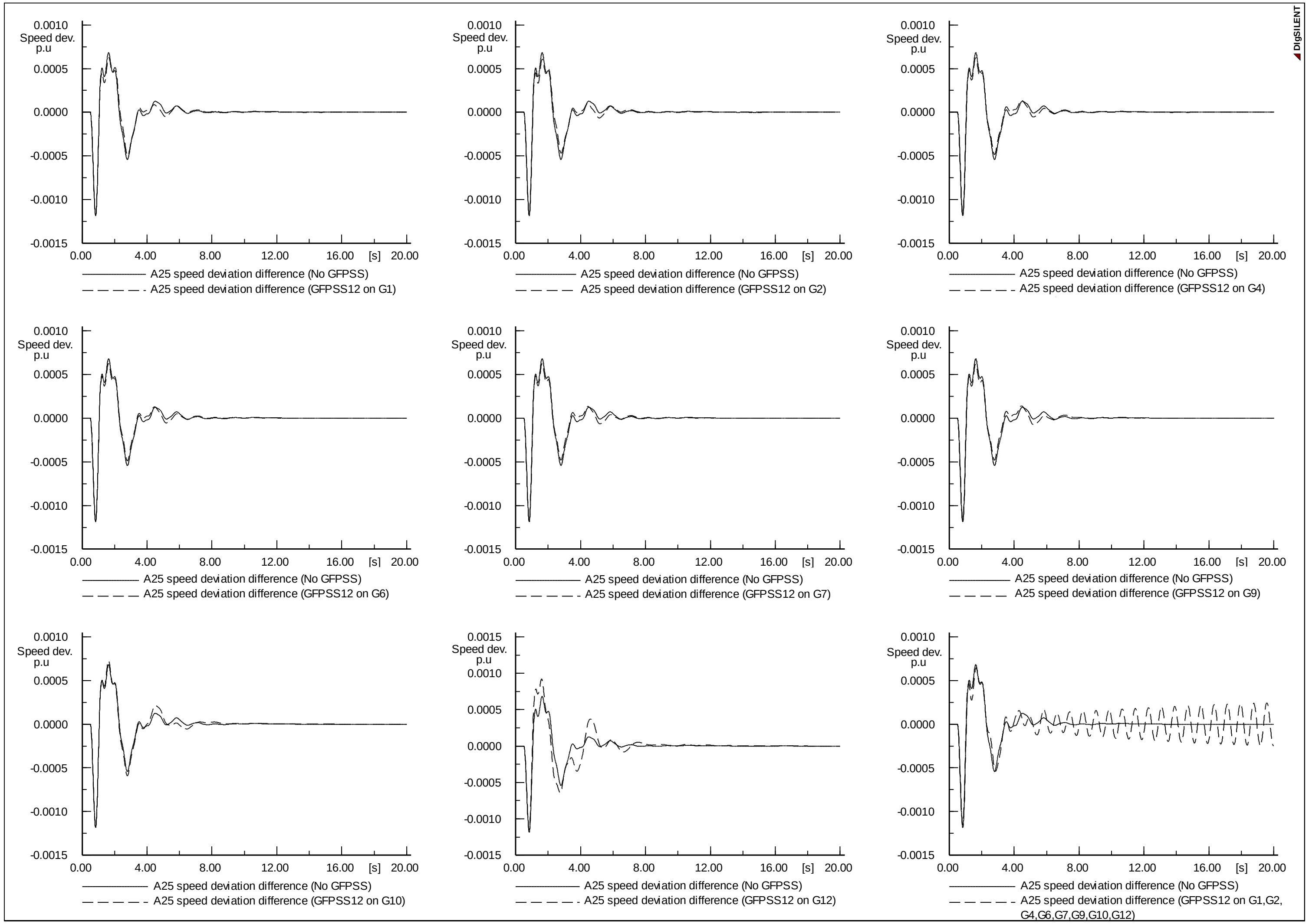

Figure 7-14: Speed deviation difference between cluster 2 and 5 with and without GFPSS scheme

B. *Performance during large disturbances*

Power systems are subject to large disturbances on daily bases. Those disturbances include faults, units' outages, tripping of a transmission line or any other types of disturbances. The cause of these disturbances varies from human errors, equipment failures or natural causes. It is, therefore, important to investigate the performance of newly developed controllers under such circumstances. Hence, in order to have a complete assessment of the performance of the developed GFPSS, the robustness and the good performance during large disturbances and rabid changes in system operation conditions are other criteria that have to be considered. For the system under consideration, a number of scenarios are put into place to cover a wide range of possible disturbances which may occur in any given power system.

The first scenario is a tripping of a heavily loaded transmission line (line 17-18, see figure (7-2)). The line is tripped after 0.5 sec from the start of the simulation and the response of the system to this large disturbance is monitored for a period of 20 sec with the implementations of different configurations to the control scheme. Figure (7-15) shows active power transfer between different clusters in the system following tripping of the mentioned line. The top left graph gives active power transfer between clusters 2 and 4 (line 46-49), the top right graph gives active power transfer between clusters 2 and 5 (line 50-51), the bottom left graph gives power transfer between clusters 3 and 4 (line 41-42) and, finally, the bottom right graph gives active power transfer between clusters 4 and 5 (line 42-52). Four different configurations for the control scheme are considered in this scenario. Those configurations are as follows:
No GFPSS signal dispatch (the solid black line), GFPSS12 signal dispatch to generator G1 in cluster 1 (the red dotted line), GFPSS12 signal dispatch to generators G1, G2 and G4 in cluster 1 (the green dotted line) and GFPSS12 signal dispatch to generators G1, G2, G4 and G9 in cluster 1 (the blue dotted line). As can be seen from figure (7-15), following the tripping of the transmission line (line 17-18) oscillations occur in the system as shown in the active power signals. However the oscillations seem to die out after a period of time and the system regains a stable equilibrium condition. Nonetheless, the effectiveness in damping those oscillations in different parts of the network varies based on the used control scheme. As mentioned previously, damping

power oscillations more effectively influences significantly the capability of power systems to transfer higher amounts of power across the transmission network. If power oscillations damping capabilities are enhanced, this increases security and reliability and allows for better utilisation of power systems.

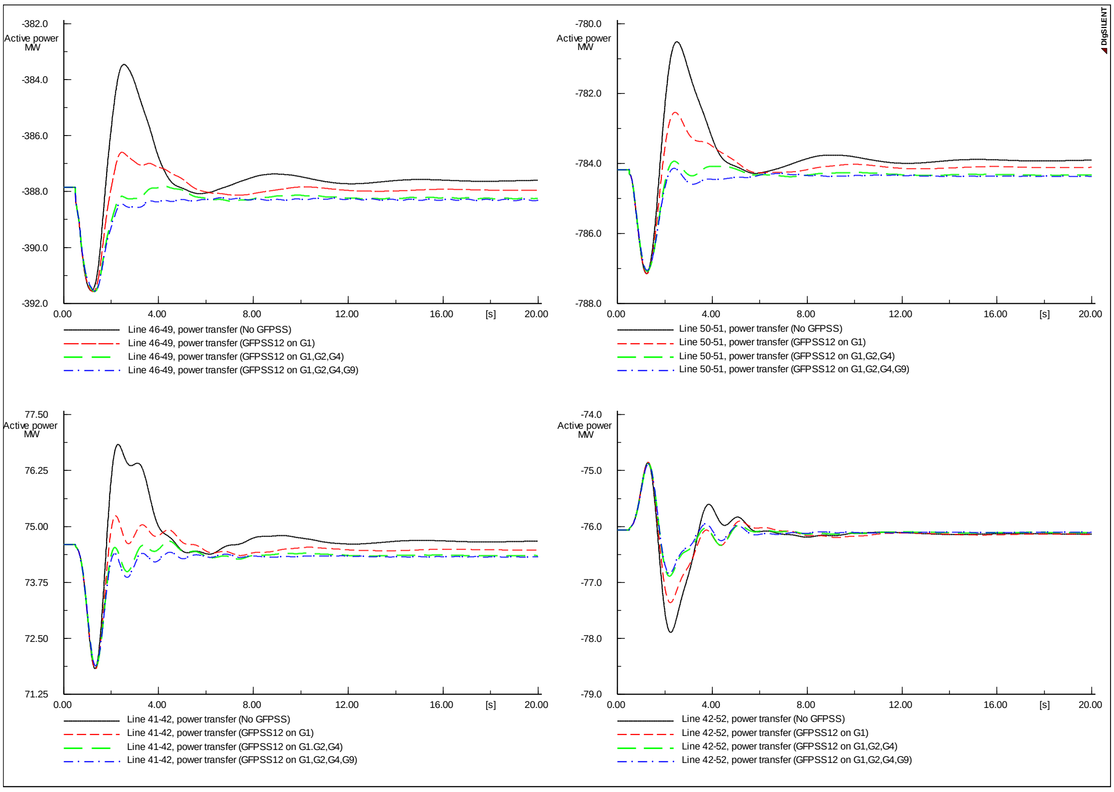

Figure 7-15: Active power transfer between different areas following tripping of line 17-18

The figure shows the robustness of the GFPSS scheme when added to the local stabilisers. It shows that oscillations are damped best when the GFPSS signals are dispatched to the four selected units (the blue dotted line). It also shows that even in the case of, say failure of GFPSS signal to reach one of the four units, the control scheme can still perform well. The advantages of being able to select a number of units to which the GFPSS signal could be dispatched gives a degree of flexibility to the control scheme and allows it to be robust and efficient.

The influence of the GFPSS scheme on the response of some of the individual units within the system is illustrated in figures (7-16) and (7-17). The two figures show the dynamic response of generators G14 and G15 (figure (7-16)) and generators G12 and

G16 (figure (7-17)) by monitoring the trajectories which their rotor angles take following the tripping of line 17-18.

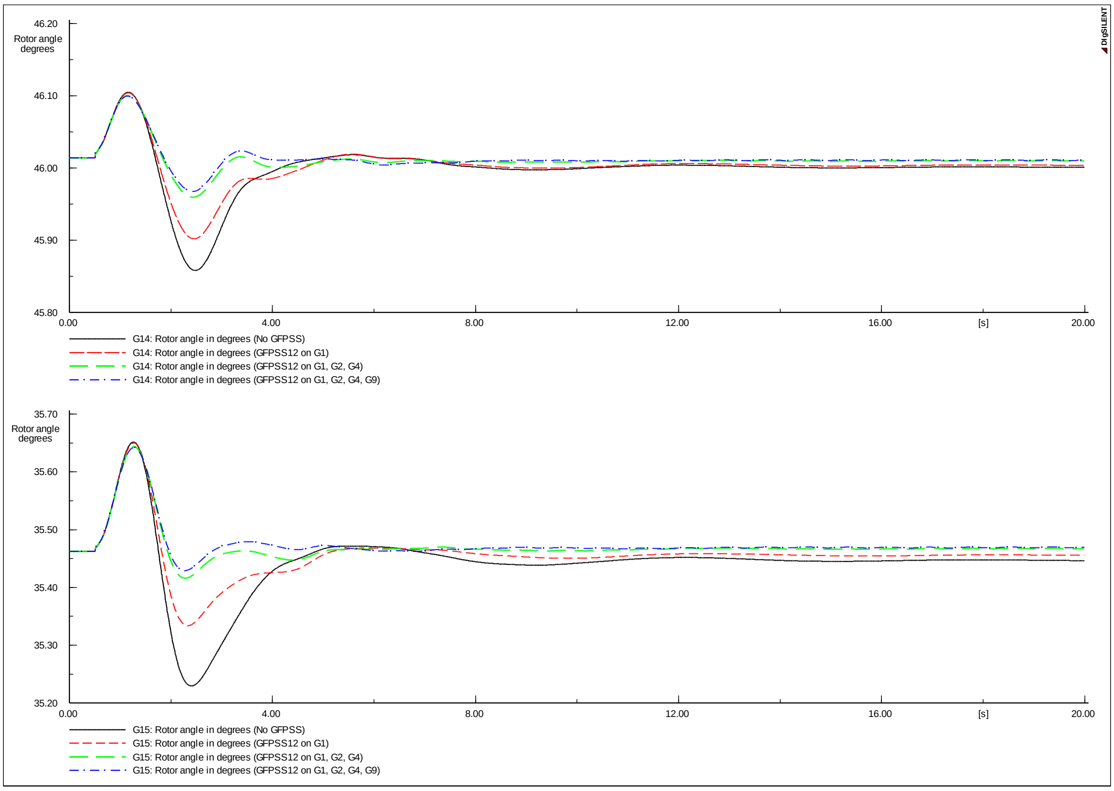

Figure 7-16: Generators' rotor angle in degrees (trip of line 17-18)

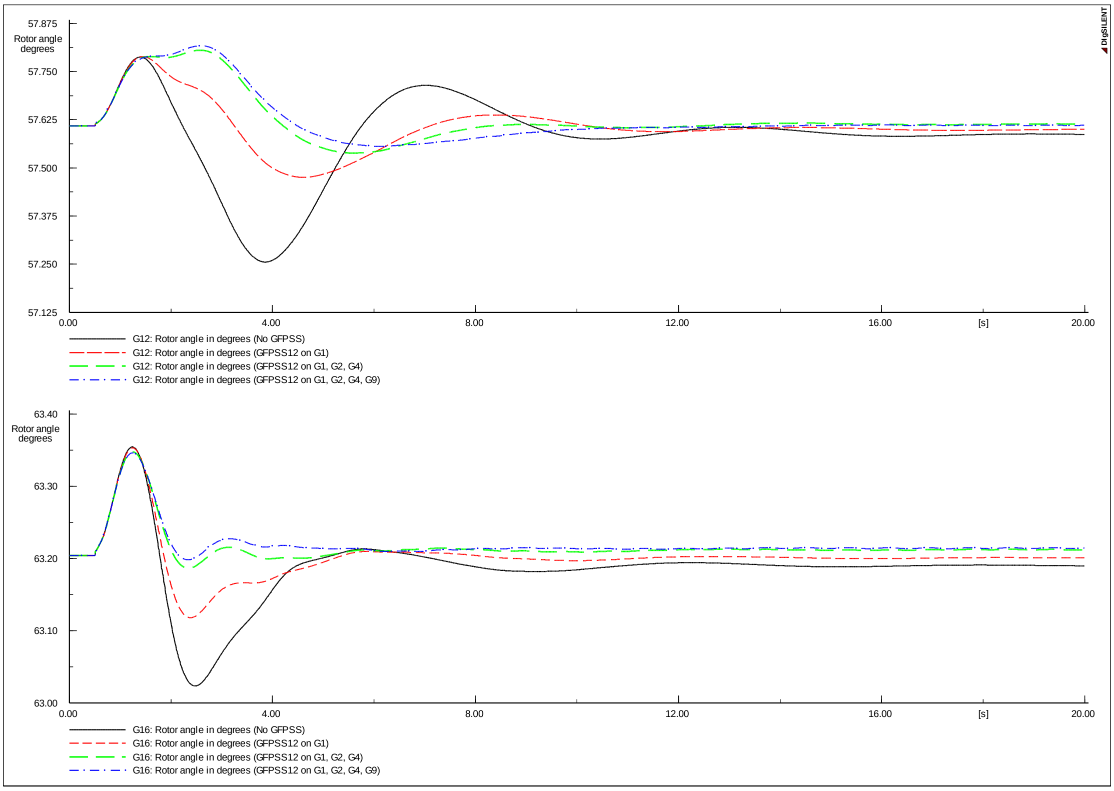

Figure 7-17: Generators' rotor angle in degrees (trip of line 17-18)

The superior performance of the GFPSS scheme is evident in both figures. Dispatching the GFPSS signal to at least one of the selected units allowed other units in widely spread area to regain stable operation following what is considered as a large disturbance in the system.

The second scenario is a tripping of another transmission line (line 16-17, see figure (7-2)). The line is tripped after 0.5 sec from the start of the simulation and the response of the system to this large disturbance is monitored for a period of 20 sec with the implementations of different configurations to the control scheme. The configurations of the GFPSS dispatch signal scheme is slightly different to the one in the previous case to illustrate the flexibility available for selectivity. Figures (7-18) and (7-19) show power transfer between the five clusters in the system (line 8-9 power transfer between cluster 1 and 2, line 1-47 power transfer between cluster 2 and 3, line 46-49 power transfer between cluster 2 and 4, line 50-51 power transfer between cluster 2 and 5, line 41-42 power transfer between cluster 3 and 4 and line 42-52 power transfer between cluster 4 and 5, refer to figure (7-2) for the network topology).

The GFPSS configuration considered in figure (7-18) are:
GFPSS12 signal dispatch to generator G1 (red dotted line), GFPSS12 signal dispatch to a combination of G1 and G10 (blue dotted line); both are compared with no GFPSS signal dispatch (solid black line).

On the other hand, in figure (7-19) different GFPSS dispatch strategies are considered and those are:
GFPSS12 signal dispatch to a combination of G1 and G9 (red dotted line), GFPSS12 signal dispatch to G1, G2, G4 and G10 (blue dotted line), and again both control strategies are with comparison to no elimination of the GFPSS from the control scheme (no GFPSS).

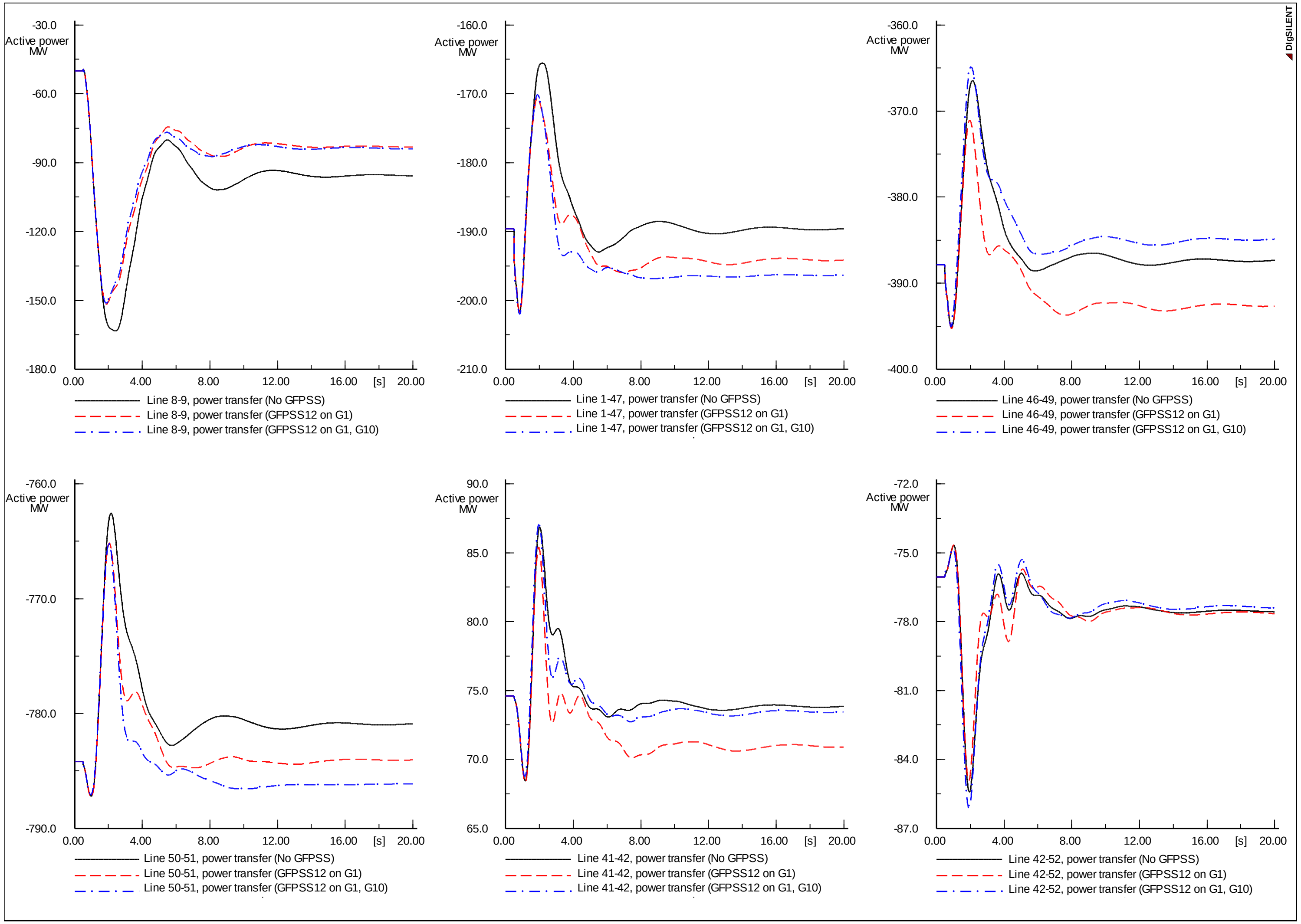

Figure 7-18: Active power transfer between different areas following tripping of line 16-17

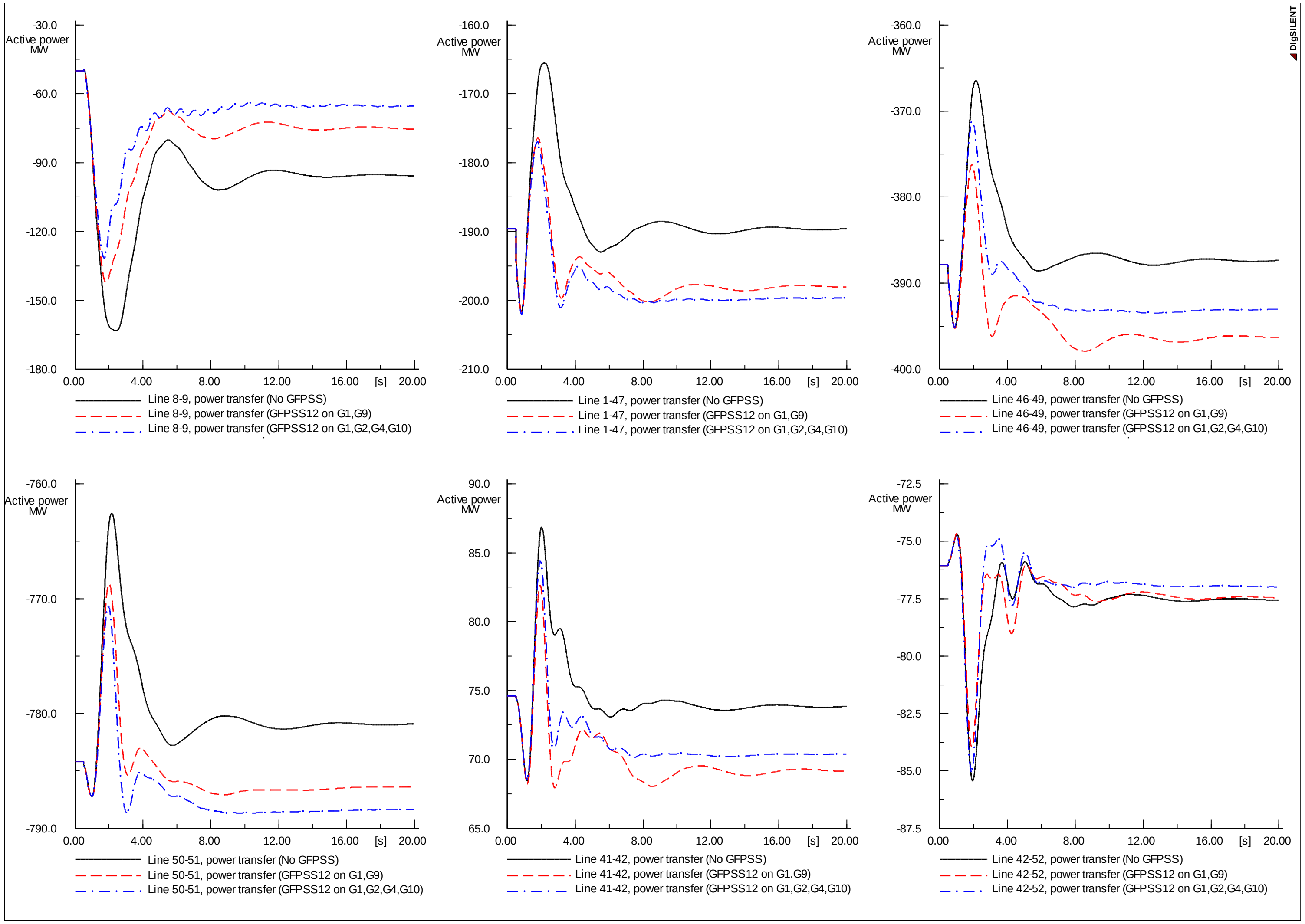

Figure 7-19: Active power transfer between different areas following tripping of line 16-17

From both figures and given a variety of GFPSS signal dispatch configurations, it can be seen that the added stabilising signals provided by the GFPSS resulted in an enhanced overall system performance. The addition of the global control signal which is produced based on wide-area information collected by the wide-area based global stabiliser allowed local controllers to act based on a wider view to the entire system. Hence, preventing wide spread system oscillations becomes more applicable and better utilisation to the transmission assets is more visible and realistic.

Once more to evaluate the effectiveness of the GFPSS scheme, the response of individual units to the disturbance under consideration is investigated. Figure (7-20) gives the dynamic behaviour of two of the large units in the system G14 and G15 following the tripping of line 16-17 for different GFPSS signal dispatch strategies. Three GFPSS configurations are illustrated in figure (7-20). Those are:

GFPSS12 signal dispatch to generator G1 (red dotted line), GFPSS signal dispatch to generators G1, G2, G4 and G10(green dotted line), GFPSS signal dispatch to generators G1, G2, G4, G6, G7, G9 and G10 (blue dotted line), all are plotted against the case with no GFPSS inclusion in the control scheme (solid black line).

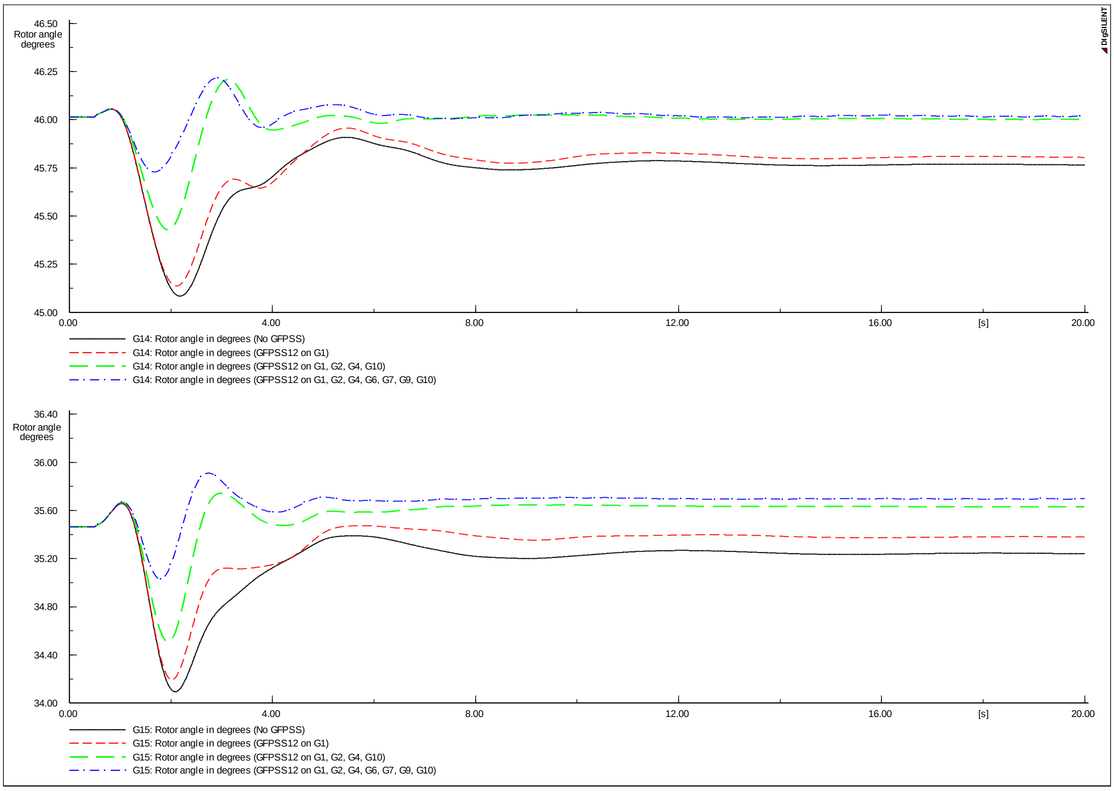

Figure 7-20: Generators' rotor angle in degrees (trip of line 16-17)

In the observations made for the two above scenarios considered for lines tripping, the effectiveness of the proposed GFPSS in providing better overall system performance is evident. The inclusion of the GFPSS control loop into the local control scheme of individual units resulted in a significant enhancement to the stability of the transmission system. Fewer oscillations with lower magnitudes are observed across the transmission corridors across the entire system which means more power could be pushed through theses corridors without risking the system security.

The third scenario for possible large disturbance is a three phase fault applied on one of the bus-bars in the system. The system is subjected to a three phase fault of duration 50 ms on bus-bar 15 (see figure 7-2). Figure (7-21) shows active power transfer across line 8-9 connecting cluster 1 and cluster 2; the GFPSS12 stabilising signal is being sent to an individual unit in each graph as shown (the units with active local PSS in their local control loops). The graph at the bottom right of figure (7-21) is when the GFPSS signal is sent to all the units at the same time. As clearly shown in the top left graph of figure (7-21), the oscillations in the active power transfer signal across line 8-9 are controllably damped more effectively when an additional stabilising control signal is included in the stabilisation control loop of generator G1 (the dotted line). The additional wide-area based signal from the proposed GFPSS enabled the power system to a robust response to the sever disturbance in comparison to the case when only local PSS stabilisers are used (the solid line). Similar results are obtained when dispatching the GFPSS signals to other individual units that have active local PSS operating in their control schemes. The graph in the bottom right of figure (7-21), however, supports some remarks made earlier when analysing the performance of the GFPSS scheme during small disturbances. It shows that it is not desirable to apply the GFPSS scheme to all units at the same time as this may result in oscillatory unstable response in the system. A good implementation strategy would be implementing the GFPSS scheme in a limited number of units to ensure that at least one unit is receiving the stabilising signal from the GFPSS.

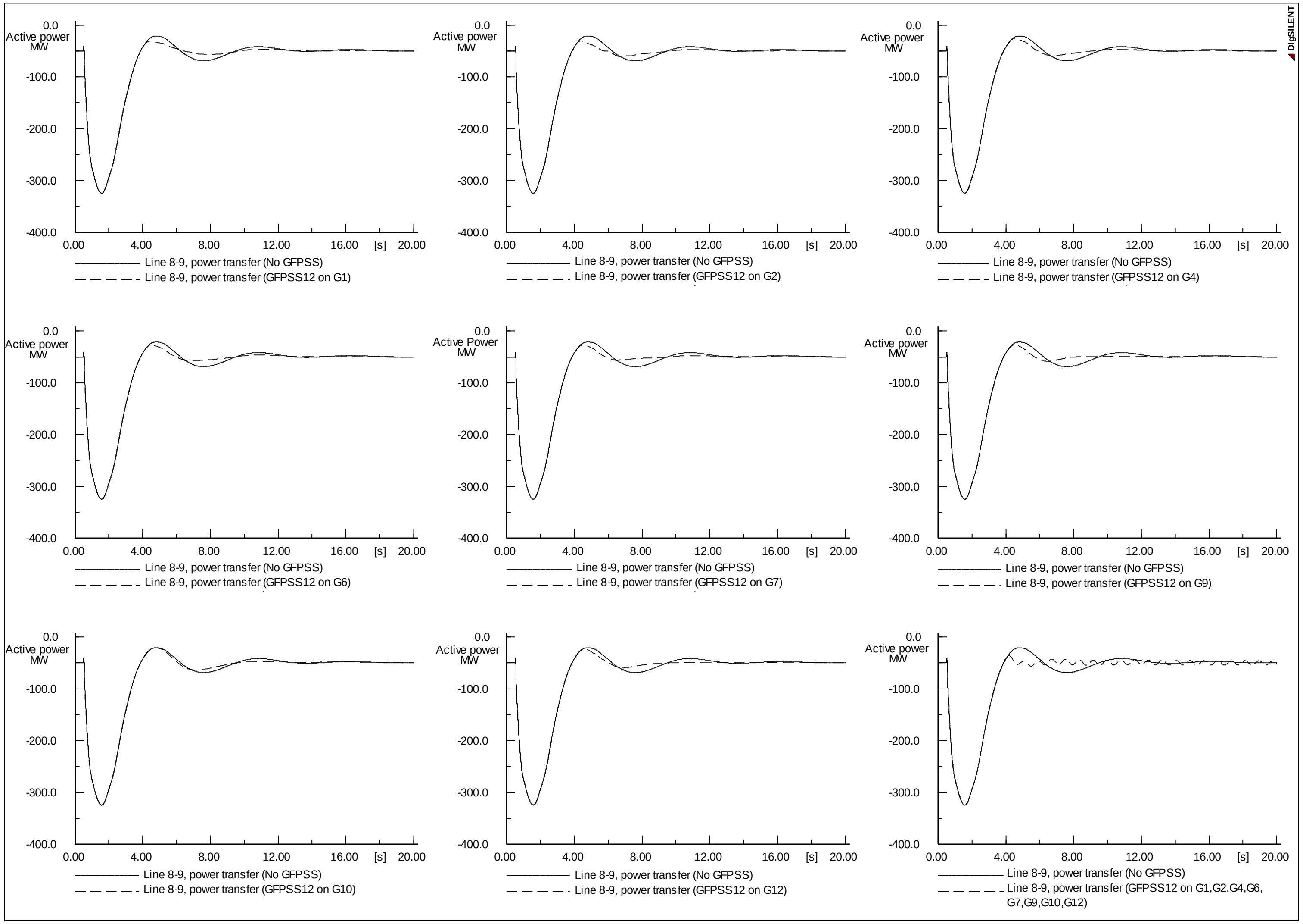

Figure 7-21: Line 8-9, active power transfer (3 phase fault on BUS 15)

As an example, figure (7-22) shows active power transfer signal across line 8-9 using different GFPSS configurations. The top graph shows active power signals across the transmission line when no GFPSS is used (black solid line), GFPSS12 signal dispatch to G1 (dotted red line) and GFPSS12 signal dispatch to both G1 and G10 (dotted green line). The bottom graph, on the other hand, shows similar control arrangement with the exception of dispatching the additional control signal from the GFPSS to G1 and G12 rather than G1 and G10 in the top graph (dotted green line)

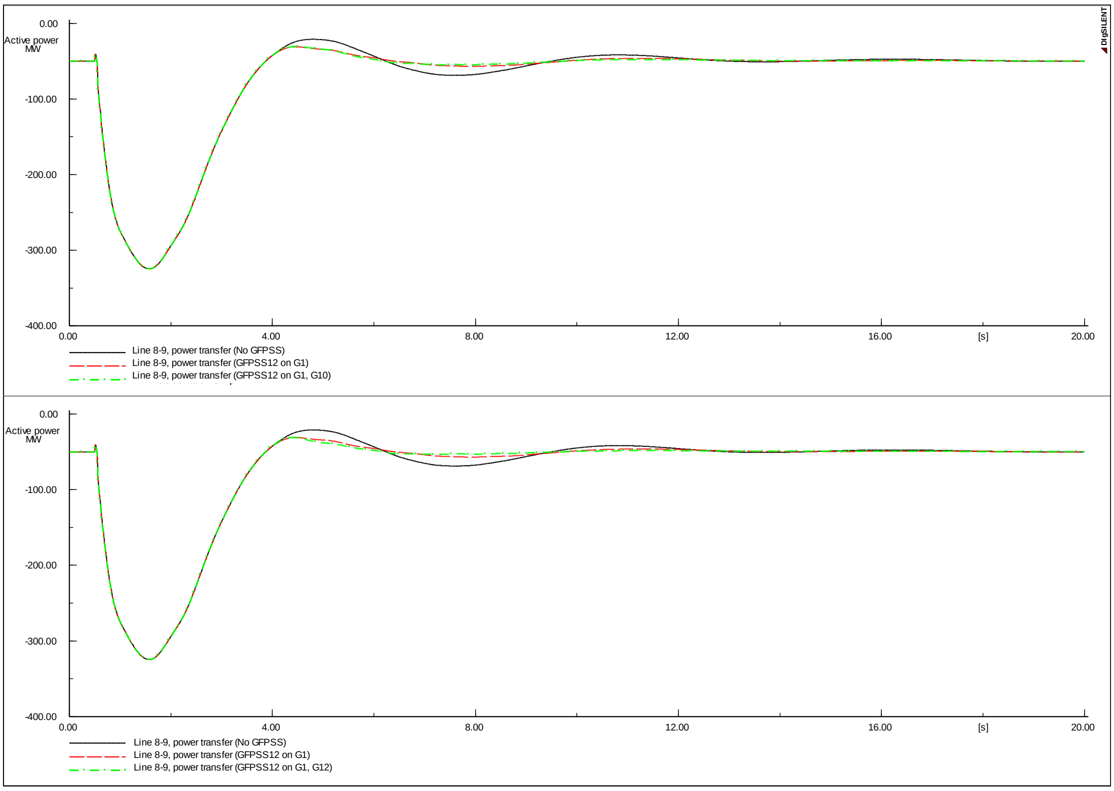

Figure 7-22: Line 8-9, active power transfer (3 phase fault on BUS 15)

The response of two individual units to the control arrangement described above (no GFPSS, GFPSS12 on G1 and GFPSS12 on G1 and G10) is illustrated in figure (7-23) which shows the rotor angles of generators G15 in cluster 5 and G16 in cluster 4. The top graph shows the swings in the rotor angle of generator G15 following the disturbance. The improved performance of the stability control scheme is obvious when comparing the two GFPSS arrangements (dotted red and blue lines) with that without implementation of the GFPSS control loop. The swings in the rotor angle are damped more effectively when incorporating the GFPSS signal into the control arrangement.

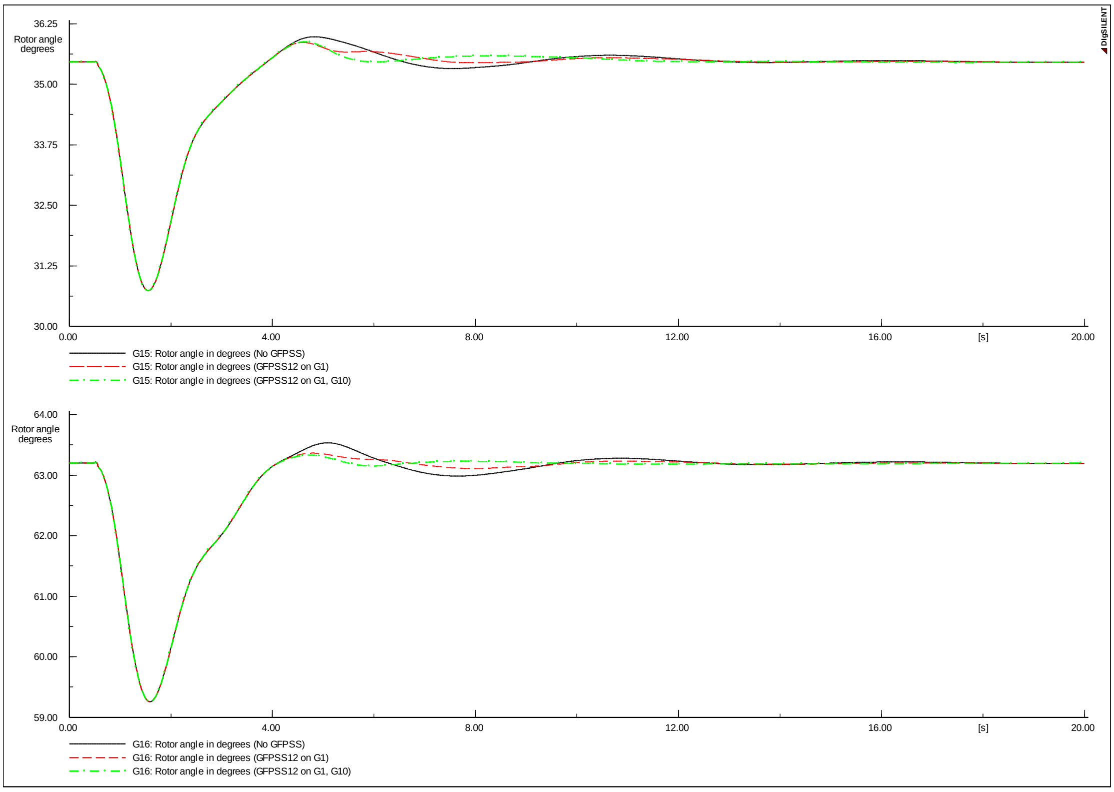

Figure 7-23: Generators' rotor angle in degrees (3 phase fault on BUS 15)

Similar observations can be made for generator G16 (bottom graph). This implies that using global signals fetched from remote parts of the network and implementing these signals to as inputs to newly designed control schemes can improve the damping of rotor angle oscillations at the local units or plants as well as improving the damping of power oscillations across interconnected areas and clusters in power systems.

7.2. Case Study 2: IEEE 39 Bus 2-Area Test System

The standard IEEE 10 generators 39-bus system consists 10 of generation units interconnected via high voltage transmission lines. The system is used previously in chapter 4 (section 4.3.2) as a study case to evaluate the clustering algorithm developed to determine coherent clusters in large interconnected power systems. As described in chapter 4, the system is formed of two coherent clusters connected via a transmission line; the line connecting BUS16 and BUS19 (line 16-19) as shown in figure (7-24). Since it is two clusters system, implementation of a single GFPSS control scheme that act as a supervisory controller between those two clusters is a visible arrangement. The input signals to this stability control scheme is derived from wide-area signals from across the entire system, namely, the differences in the weighted average speed deviation signals of the units in both clusters and the deviations in the active power transfer across the transmission line connecting both clusters (line 16-19). The acquisitions of those signals are described by equations (6.9) to (6.11). The system is modelled using the dynamic simulation programme DIgSILENT (*Digital Simulator for Electric Network*). All generation units are equipped with continuous stability control schemes that consist of excitation systems controls, speed governor controls and power system stabilisers. The GFPSS scheme is implemented taking into account some of the observations made in the previous study case. The GFPSS signal will only be applied to few selected units as it is shown that dispatching the GFPSS signal to all units at once has a rather negative impact on the stability of the system. In this case, generator G1 will be the focus of the GFPSS scheme, being the reference and largest unit in the system. Other units are generator G7 and G8 which are selected based on extensive simulations that led to conclude that the control scheme works best when those units are considered. Similarly to the previous case, the controller performance is tested for both small disturbances and large disturbances during a number of operating scenarios.

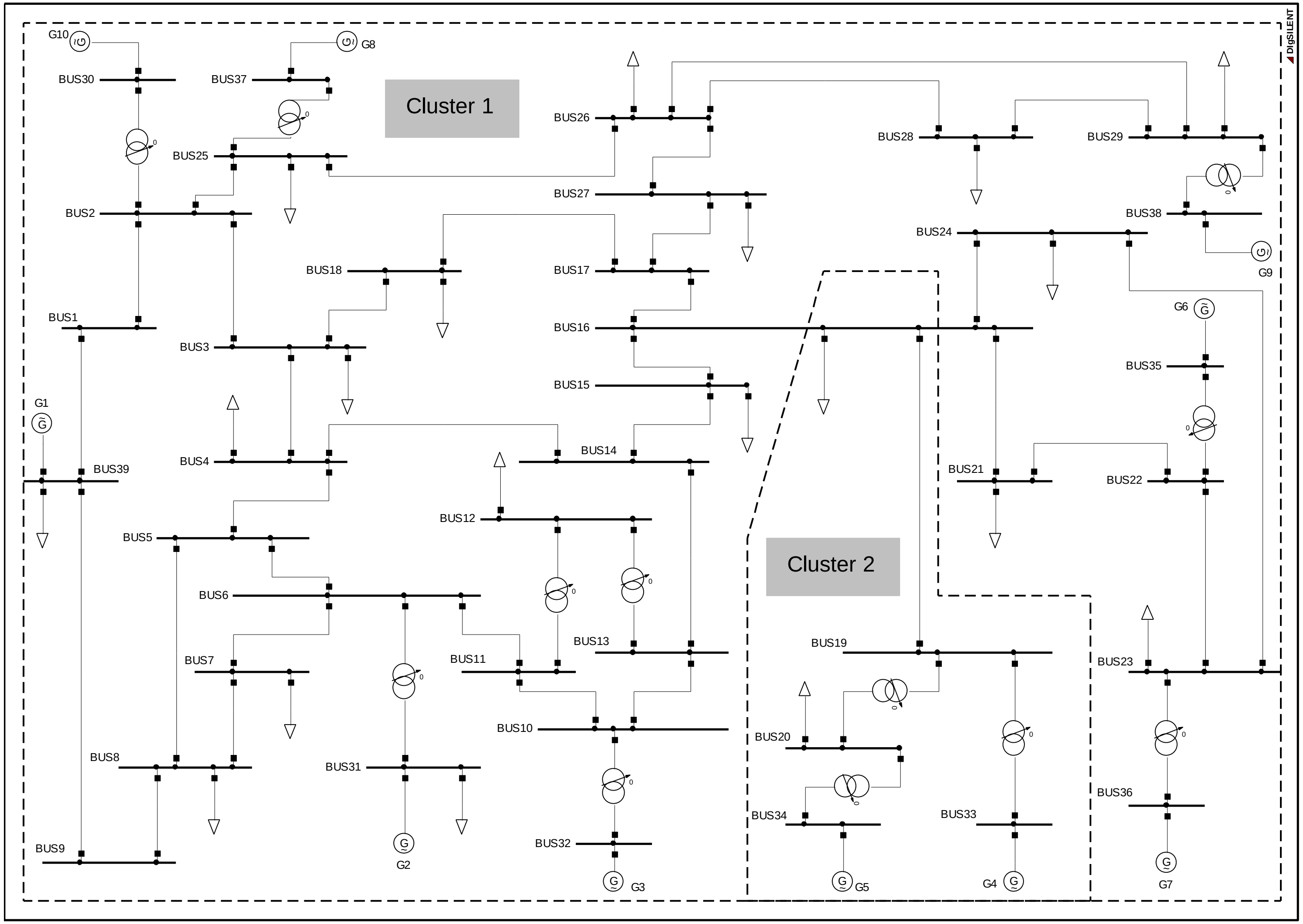

Figure 7-24: IEEE 10 machines 39 bus / two clusters system

A. *Performance during small disturbances*

For small signal disturbance, a pulse of 5% magnitude at the voltage reference of the largest generator G1 located in cluster 1 for a time period of 50 ms. The system's response to this disturbance is then monitored under a variety of available control arrangements. The system's behaviour following the disturbance can be viewed in a number of variables that display the dynamic response of the system during and following the occurrence of the event. A good dynamic variable that can show the response of the system based on the used control arrangement is the difference in the weighted average speed deviation signal between cluster 1 and 2 as shown in figure (7-25) bellow. The figure shows four different control arrangements with regard dispatch of the control signal from the GFPSS. The top left graph is when GFPSS control signal is applied to generator G1 (red dotted line), top right graph is when GFPSS control signal is applied to generator G7 (red dotted line), bottom left graph is when GFPSS control signal is applied to generator G8 (red dotted line) and bottom right graph is when GFPSS control signal is applied to a combination of the three units at once G1, G7 and G8 (red dotted line). The four control arrangements are compared to the base case when there is no GFPSS controller in service (black solid line). The aim of the stabilising control strategy is to minimise any oscillations in the system and to maintain stable equilibrium point of operation in the shortest possible time. The GFPSS inclusion into the control scheme seems to have achieved those goals as can be seen from the figure. Best GFPSS control performance is obtained when the control signal is directed to generator G1, being the largest reference unit in the system. A good system response is also observed when directing the signal to either generator G7 or G8 as oscillations are damped more effectively. Dispatching the signal to more than one unit at the same time insures that at least one of these units receives the wide-area based control signal; hence, provides the required additional damping force which is needed to enhance the system's stability.

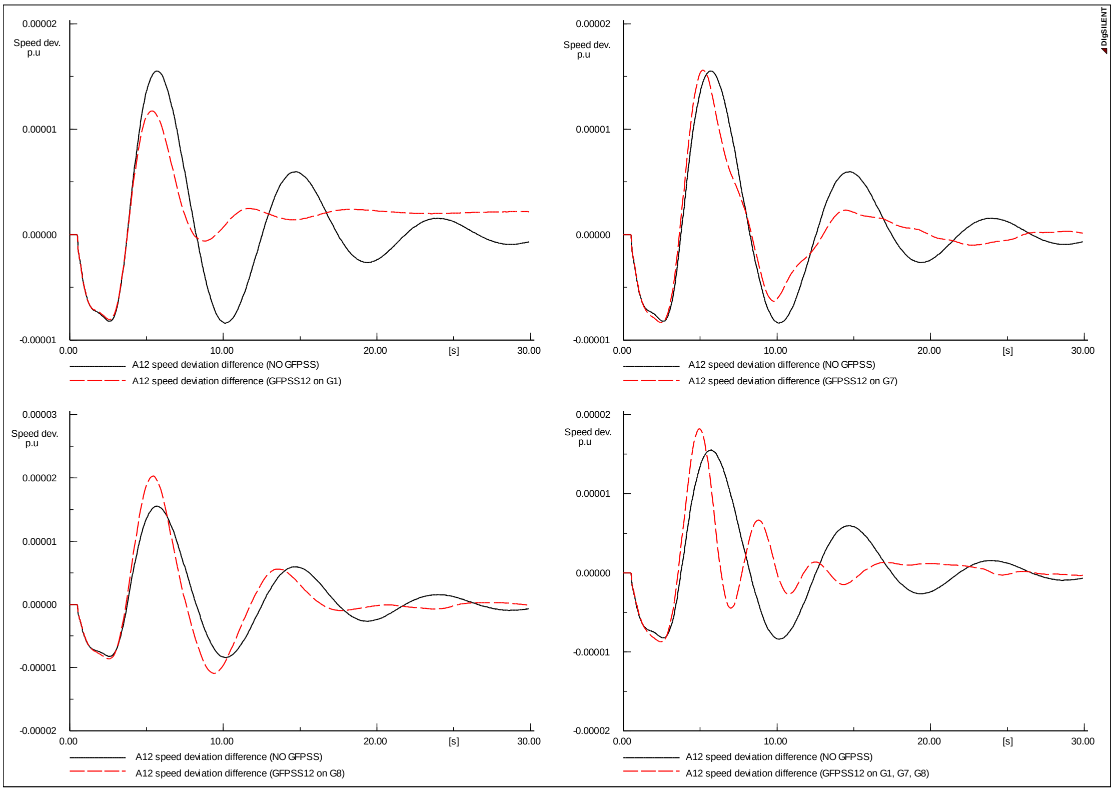

Figure 7-25: Speed deviation difference between cluster 1 and 2 (pulse on voltage reference of generator G1)

Providing the additional damping to the system allows for better transfer capabilities. This can be seen in the power transfer signals across the transmission system. Figure (7-26) shows active power transfer across the transmission line connecting clusters 1 and 2 (line 18-19, see figure (7-24)). The figure follows similar control arrangements to that described for figure (7-25). As oscillations between the two clusters are controllably damped more quickly using the GFPSS arrangements, more power can be transferred across the transmission system with a high degree of confidence in system's security. The GFPSS strategy increases the stability limits of the system which goes hand in hand with security and reliability improvement. As a result, it allows for better utilisation and more flexibility of the transmission networks, an important and necessary requirement for today's power system.

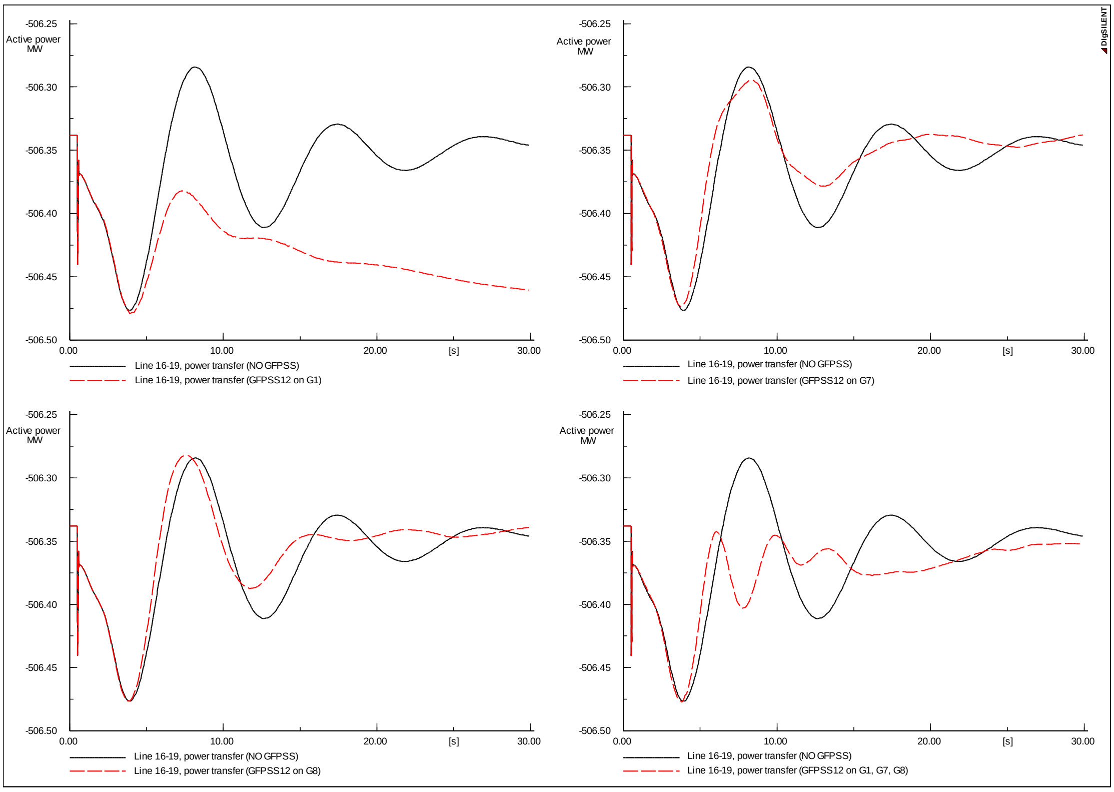

Figure 7-26: Line 16-19, active power transfer (pulse on voltage reference of G1)

To evaluate the impact of the GFPSS different arrangements on individual units in the system, figure (7-27) displays the dynamic response of generator G1 to the encountered disturbance. The response of the unit is captured in the trajectory which its rotor angle follows following the disturbance. The figure shows the unit response when the GFPSS signal is dispatched to three different individual units each time. The graph in the top is when the GFPSS signal is sent to G1, the graph in the middle is when the GFPSS signal is sent to G7 and the graph in the bottom is when the GFPSS signal is sent to G8 (all responses are illustrated in red dotted lines). Again, the three cases are compared with the base case when no GFPSS controller is put into service (the black solid lines). As can be seen from the figure, the rotor angle of the largest unit in the system seems to swing less (both in magnitude and duration) when there is a GFPSS controller acting between the two clusters in the system under study. The unit regains a stable equilibrium point of operation very quickly. It also experiences fewer oscillations in the kinetic energy stored in its rotor when a GFPSS control signal is sent to any of the selected units. The unit response is also displayed when combinations of GFPSS signal dispatch strategies to the selected generators are put into place; this is shown in figure (7-28).

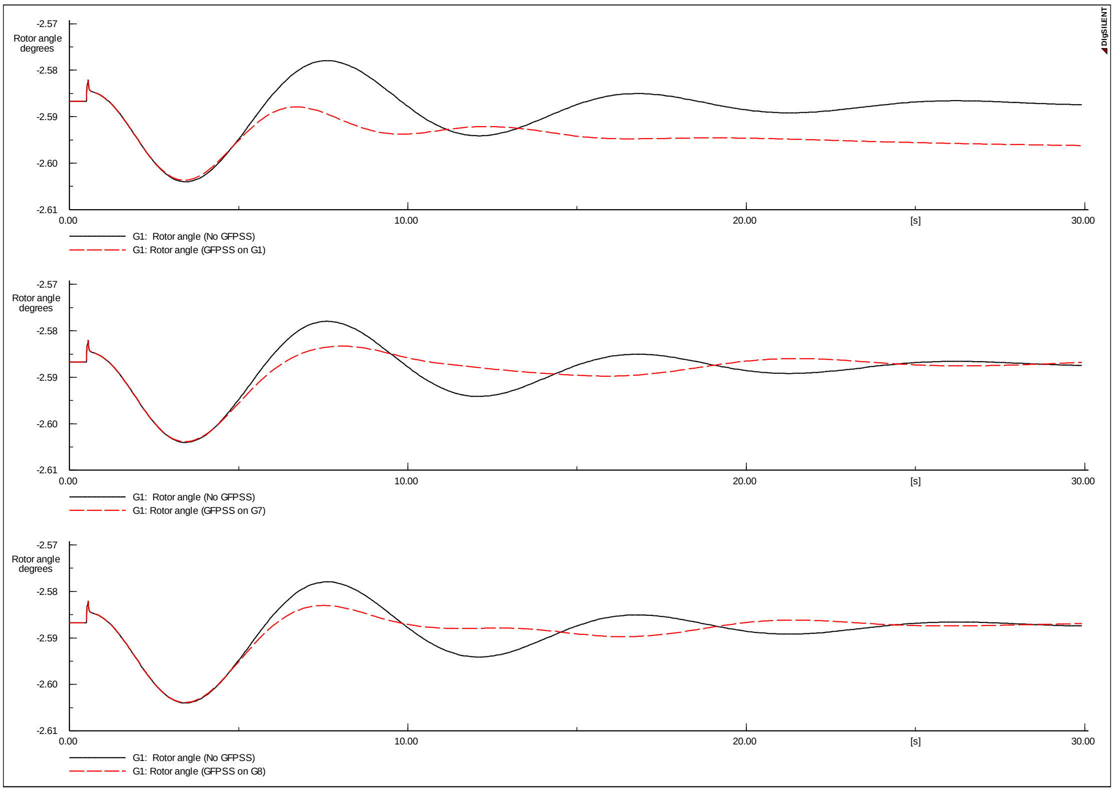

Figure 7-27: Rotor angle of G1 in degrees (pulse on voltage reference of G1)

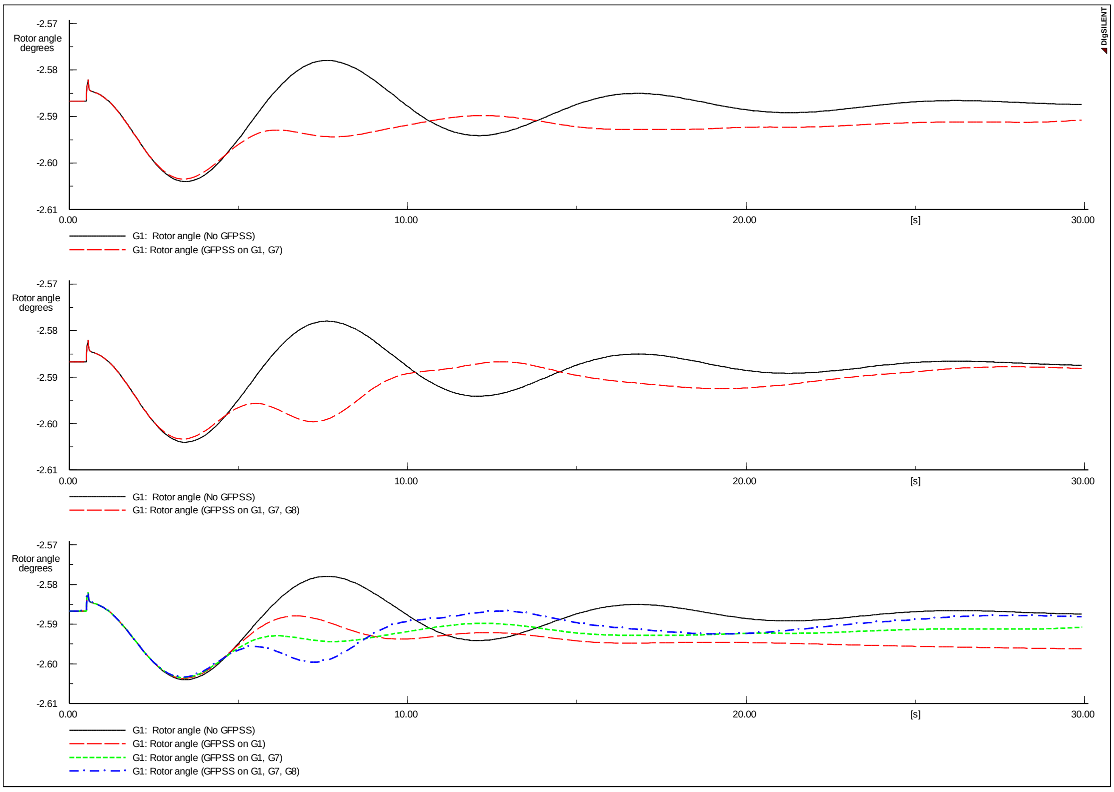

Figure 7-28: Rotor angle of G1 in degrees (pulse on voltage reference of G1)

The top graph in figure (7-28) shows the rotor response of G1 when GFPSS signals are applied to both G1 and G7, the middle graph is when the GFPSS signal is applied to a combination G1, G7 and G8 and the bottom graph plots latter control arrangements with the case when a GFPSS signal is applied to G1. The black solid line is always for the base case when there is no active GFPSS. With comparison to the case when there is no GFPSS active between the two clusters, it is clear that any control arrangement which includes a GFPSS scheme into the stabilising loops of individual units would result in a better system response and enhanced control performance.

B. *Performance during large disturbances*

The performance of the GFPSS scheme in this study case is also tested for large power system disturbances and rabid sudden changes in system conditions to insure its robustness and its satisfactory performance during such operating conditions. A number of scenarios are considered to cover a wide range of possible disturbances which may occur in any real power system. Included in this section is a case of a transmission line outage and a case of a three phase fault at one of the system buses as will be explained.

The first scenario is a tripping of a transmission line (line 17-18, see figure (7-24)). The line is tripped after 0.5 sec from the start of the simulation and the response of the system to this large disturbance is monitored for a period of 30 sec with the implementations of different configurations to the control scheme. The generators considered for implementation of the GFPSS scheme are the same as for the case of small disturbances explained above. Figure (7-29) shows the difference in the weighed speed deviation signals between cluster 1 and 2. The top left graph gives the system response when the GFPSS scheme is applied to generator G1, the top right graph is for the system response when the GFPSS scheme is applied to generator G7, the bottom left graph is for the system response when the GFPSS scheme is applied to generator G8 and the bottom right graph is for the system response when the GFPSS scheme is applied to the three units combined G1, G7 and G8. The red dotted line in figure (7-29) is for the system response when there is a GFPSS active and is compared with the case when only local power system stabilisers are available at the local plant (the black solid lines). With comparison to the case when only local PSS are acting to provide the stabilisation signal based on the locally available feedback signals, it is obvious that adding the wide-area based GFPSS loop into the stabilisation control loop provides more oscillation damping capabilities. This is clear for any GFPSS control arrangement given in figure (7-29). The difference in the weighted speed deviation signals between cluster 1 and 2 settle more quickly (it takes less time for the oscillations to damp out) with fewer oscillations when there is a GFPSS scheme put into place.

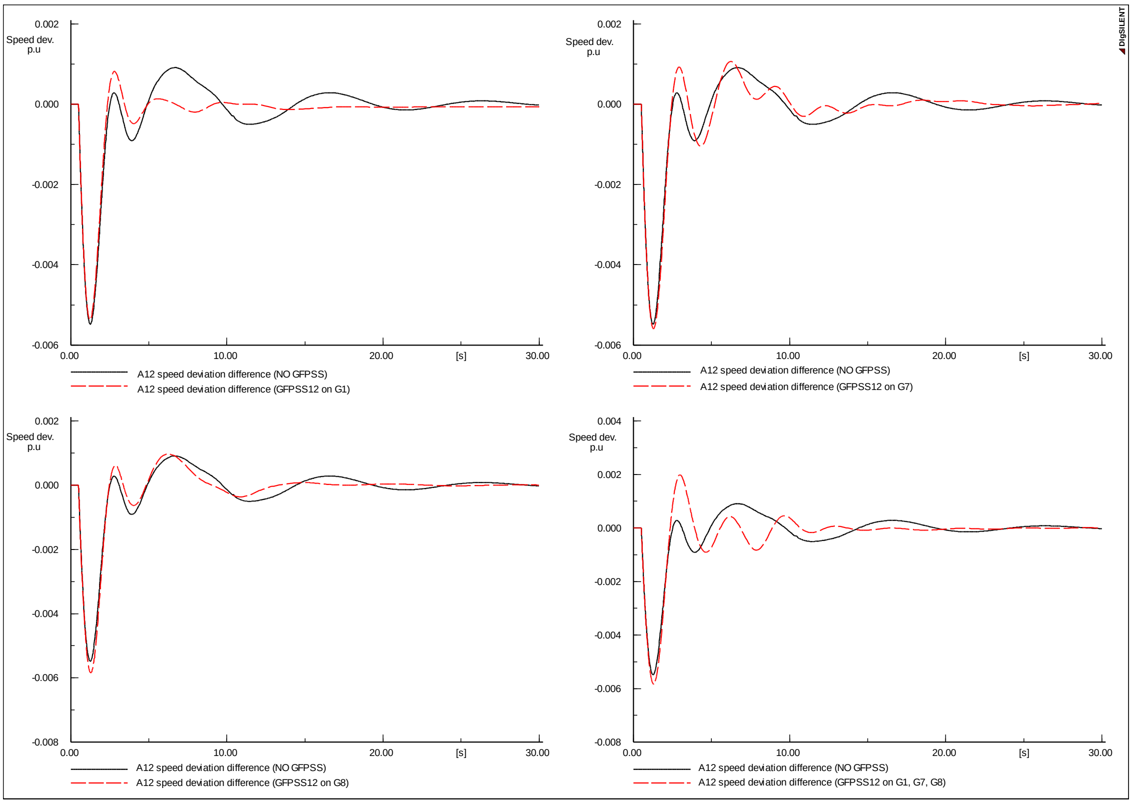

Figure 7-29: Speed deviation difference between cluster 1 and 2 (tripping of line 17-18)

The improvement in oscillation damping capabilities can also be seen in the signals of active power transfer between the two clusters as shown in figure (7-30). The figure shows active power transfer across the transmission line connecting cluster 1 and 2 (line 16-19). The control arrangement for this figure is the same as the one described above for figure (7-28). The oscillations between the two clusters are controllably damped more effectively using the GFPSS scheme. Being able to damp the oscillations between wide spread connected areas improves the transmission stability and allows for better exploitations for transmission assets. Figure (7-30) also shows that it is recommended to have the GFPSS scheme implemented to at least 2 units in the system to provide a degree of certainty that the additional wide-area based control signal would be active at one of the units.

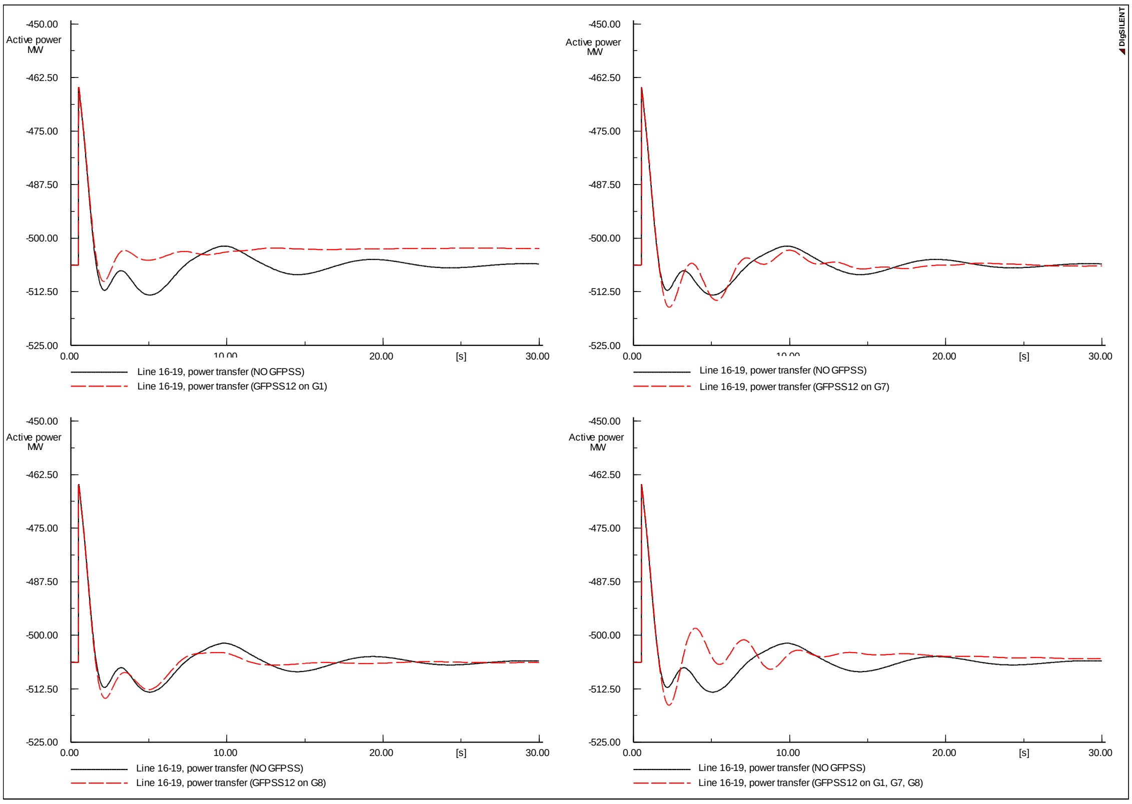

Figure 7-30: Line 16-19, active power transfer (tripping of line 17-18)

The response of the individual units the encountered disturbance is illustrated in figure (7-31) and figure (7-32) bellow. Both figures show the rotor angles of the system's units in degrees. Figure (7-31) shows a comparison of the dynamic response of all units in the system (G1 to G9) when the GFPSS control signal is added to the stabilisation control loop of generator G1 (depicted by the red dotted lines) with the response of the units when only local PSS are activated (shown by the black solid lines). As can be seen, the oscillations in all units' rotors seem to be enhanced significantly when a GFPSS scheme is put into place to provide additional stabilising control signal through the excitation system of generator G1. All units tend to regain stable operating equilibrium more quickly following the tripping of the transmission line when the GFPSS signal is dispatched. Considering, for example, the trajectory that the rotor angle of generator G1 takes (top left graph of figure (7-31)) as the disturbance occur and comparing the two cases (with and without GFPSS), it is obvious the significant improvement that the GFPSS scheme can provide when added to local control strategies.

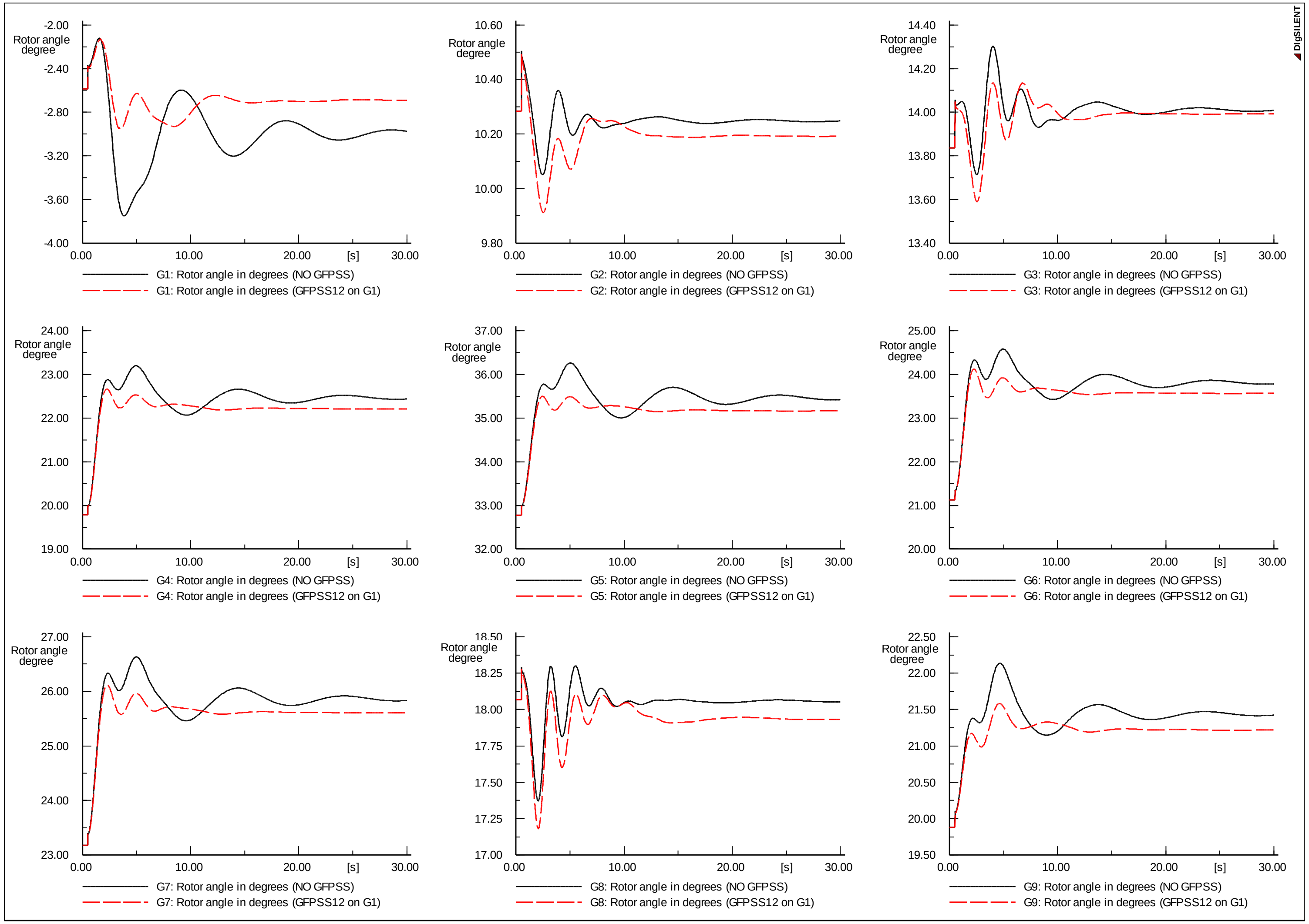

Figure 7-31: Rotor angle of generators G1 to G9 in degrees (tripping of line 17-18 / GFPSS12 on G1)

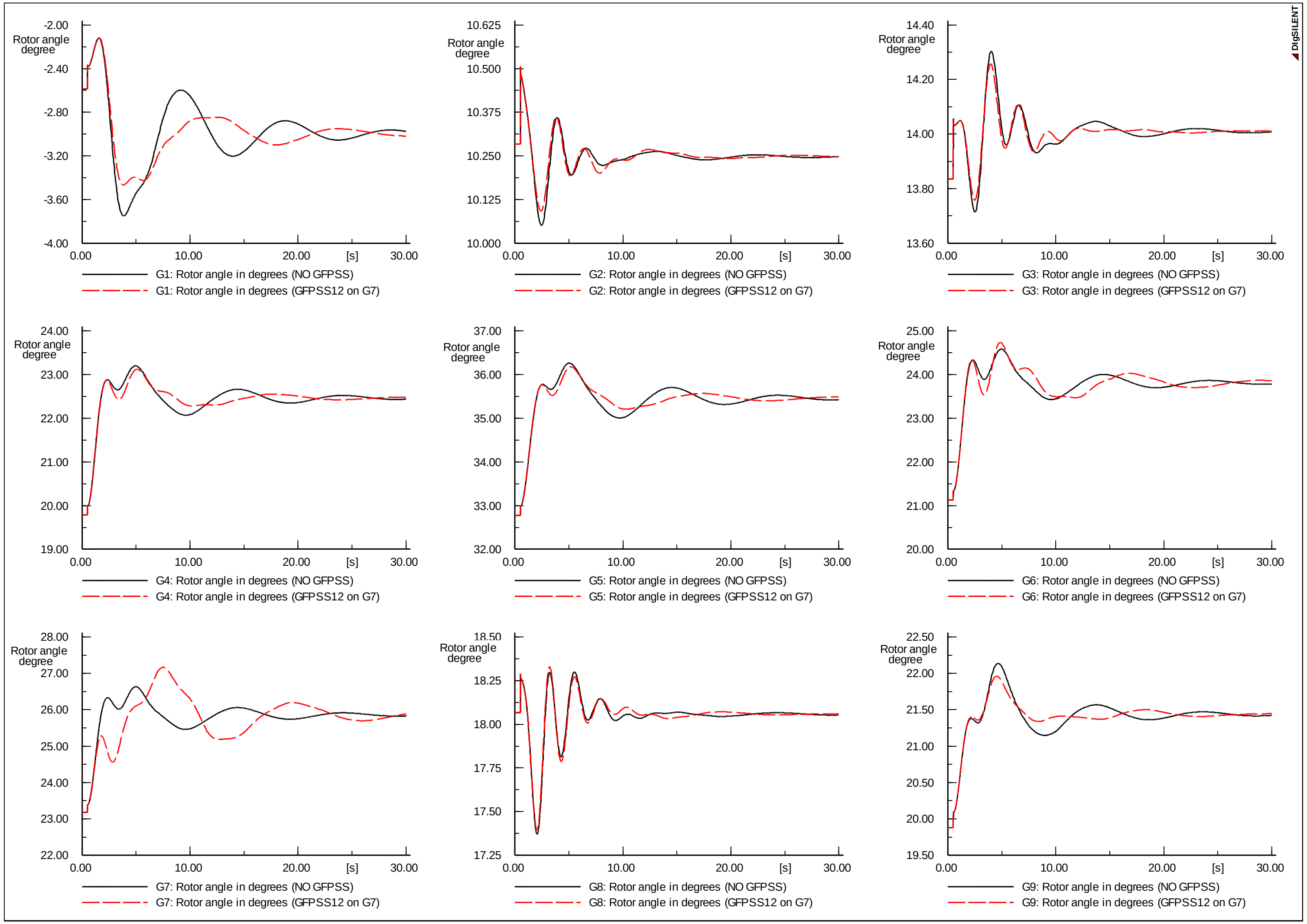

Figure 7-32: Rotor angle of generators G1 to G9 in degrees (tripping of line 17-18 / GFPSS12 on G7)

Similar observation can be made when monitoring the rotor angles of the system's units during the disturbance giving that the GFPSS scheme us applied to the control system of generator G7 as shown in figure (7-32) with the exception of the response of generator G7 itself. Nonetheless, as an overall system performance, the GFPSS scheme seems to improve the stability of the system as a whole when applied to any of the selected units as described in figure (7-29) and (7-30) above.

The second large disturbance scenario is a three phase fault applied on one of the bus-bars in the system. The system is subjected to a three phase fault of duration 50 ms on bus-bar 1 (BUS 1, see figure (7-24)). The dynamic response of the system to this large disturbance is monitored for a period of 30 sec with the implementations of different configurations to the GFPSS control scheme, similar to those considered in the previous events (i.e. the GFPSS wide-area base control signal is dispatched to generators G1 or G7 or G8 or to a their combination). Figure (7-33) shows active power transfer across the transmission line (L9-36, see figure (7-24)).

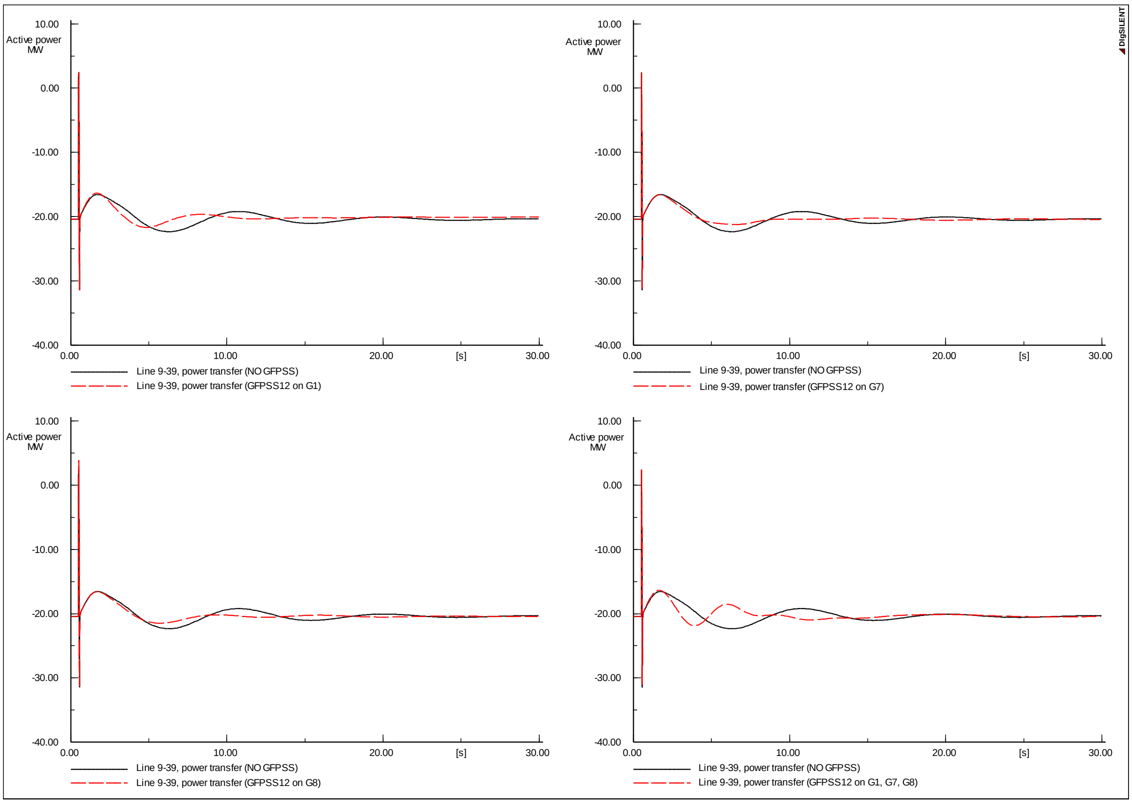

Figure 7-33: Line 9-36, active power transfer (3 phase fault on BUS 1)

The black solid line represents active power transfer via the considered line when only local stabilisers are available at the local stabilisation control loop of the generators. The red dotted line, on the other hand, represents active power transfer across the transmission line when a GFPSS control loop is added as a provider to a wide-area based stabilising control signal to one or more of selected units. As can be seen from figure (7-33), a considerable improvement in damping the oscillations in the transmission corridor caused by the occurred fault is achieved as a result of the additional stabilisation control loop (the GFPSS loop). The system stability following the disturbance is enhanced regardless to which of the three units (G1, G7 and G8) the GFPSS signal is sent. Dispatching the GFPSS signal to more than one selected unit (bottom right graph in figure (7-33)) guarantees that the stabilisation effect on the system will be assured since at least one of these units will receive the additional control signal. The stabilising effect of the additional GFPSS loop can also be seen in the difference in the weighted speed deviation signals between cluster 1 and 2, shown in figure (7-34)

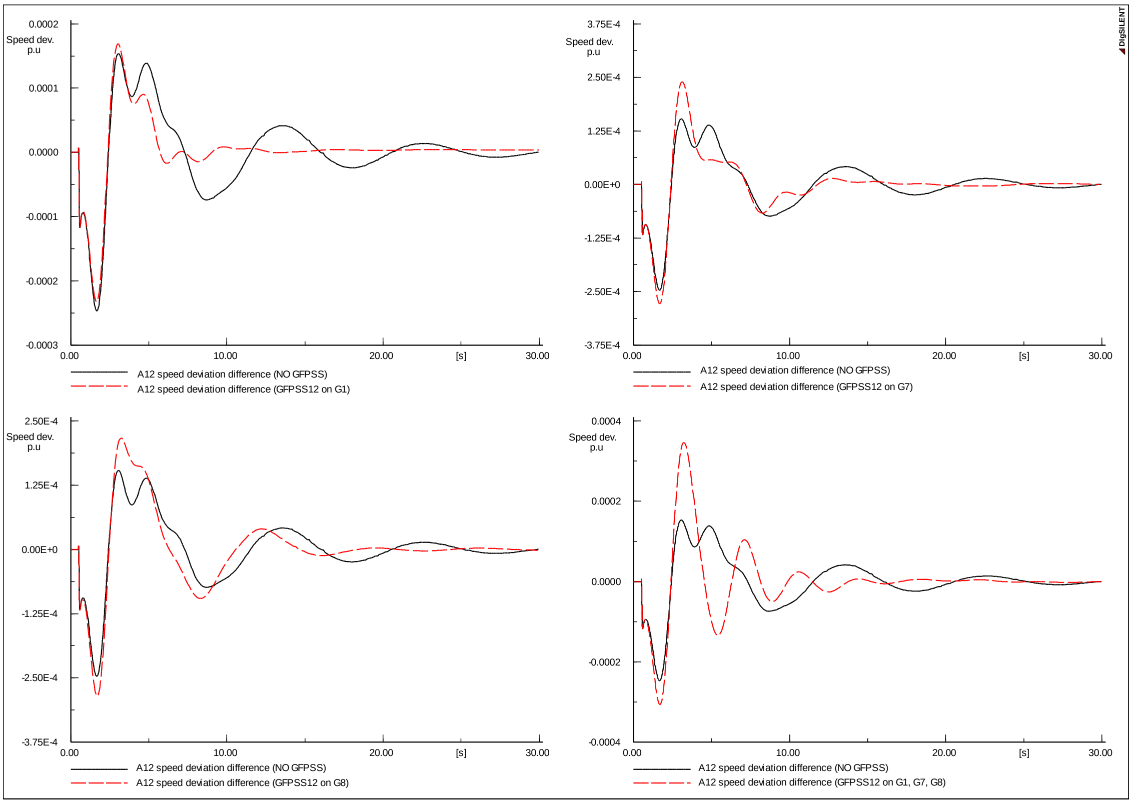

Figure 7-34: Speed deviation difference between cluster 1 and 2 (3 phase fault on BUS 1)

The red dotted line represents the difference of the weighted average speed deviation signals of the generators in cluster 1 and 2 derived based on equations (6.9) and (6.10) when a GFPSS scheme is implemented and is compared with the case with no GFPSS in place. The signals give an insight in how the generators in both clusters respond to the disturbance. Figure (7-34) supports the observations made for figure (7-33) and it also shows that better control arrangement is achieved when dispatching the GFPSS signal to generator G1. Although implementing the GFPSS scheme on generators G7 and G8 is less effective than implementing it on G1, the overall performance of the system is still better with the addition of the GFPSS control loop.

The superior performance of the GFPSS scheme when implemented on G1 can be seen clearly in the speed deviation signals of the individual units shown in figure (7-35). The figure shows the response of all units in the system (G1 to G9) when the GFPSS signal is sent to generator G1 (the red dotted line) with comparison to the system’s response with no additional GFPSS control loop (the solid black line). It can be seen that the speed deviations of all units settles more quickly in a shorter time frame when implementing the GFPSS scheme. This implies that all units in the system are able to regain a stable post-fault operating equilibrium in a much improved manner with comparison to the case with no GFPSS. The ability of all units to maintain their stable equilibrium more effectively reflects positively on the overall performance of the system as shown in figures (7-34) and (7-33).

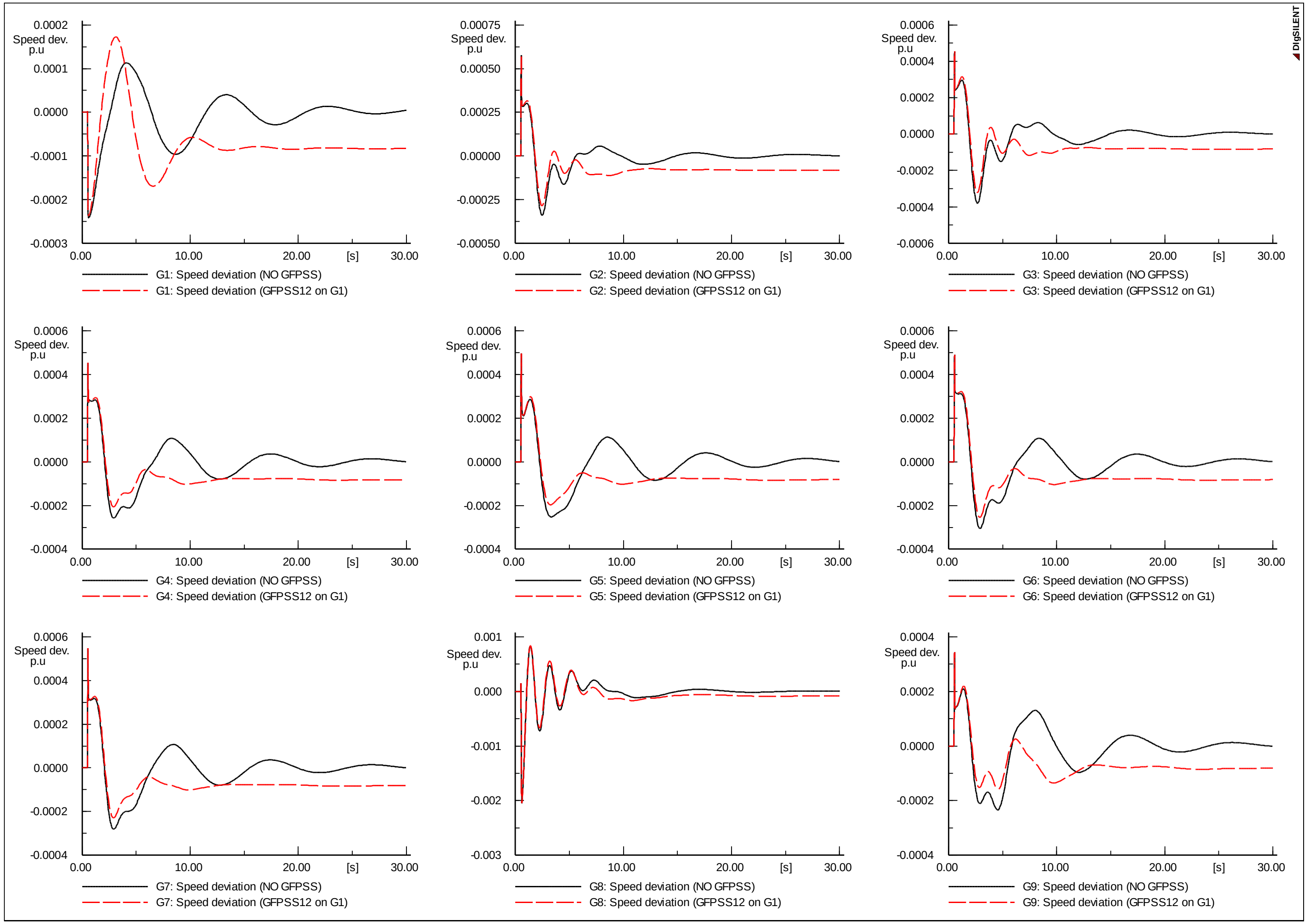

Figure 7-35: Speed deviations of generators G1 to G9 (3 phase fault on BUS 1 / GFPSS12 on G1)

To allow for better comparison between the different control arrangements, figure (7-36) shows generator G1 response when implementing four different GFPSS implementation strategies compared with the case of no GFPSS. The response of G1 is displayed in its rotor angle (top graph) and its speed deviation signals (bottom graph). The top graph shows that the rotor angle of generator G1 oscillate less (both in magnitude and duration) when there is a GFPSS control loop acting between the two clusters. Less oscillations in the unit's rotor angle illustrates its ability to accommodate the changes caused by the disturbance more effectively.

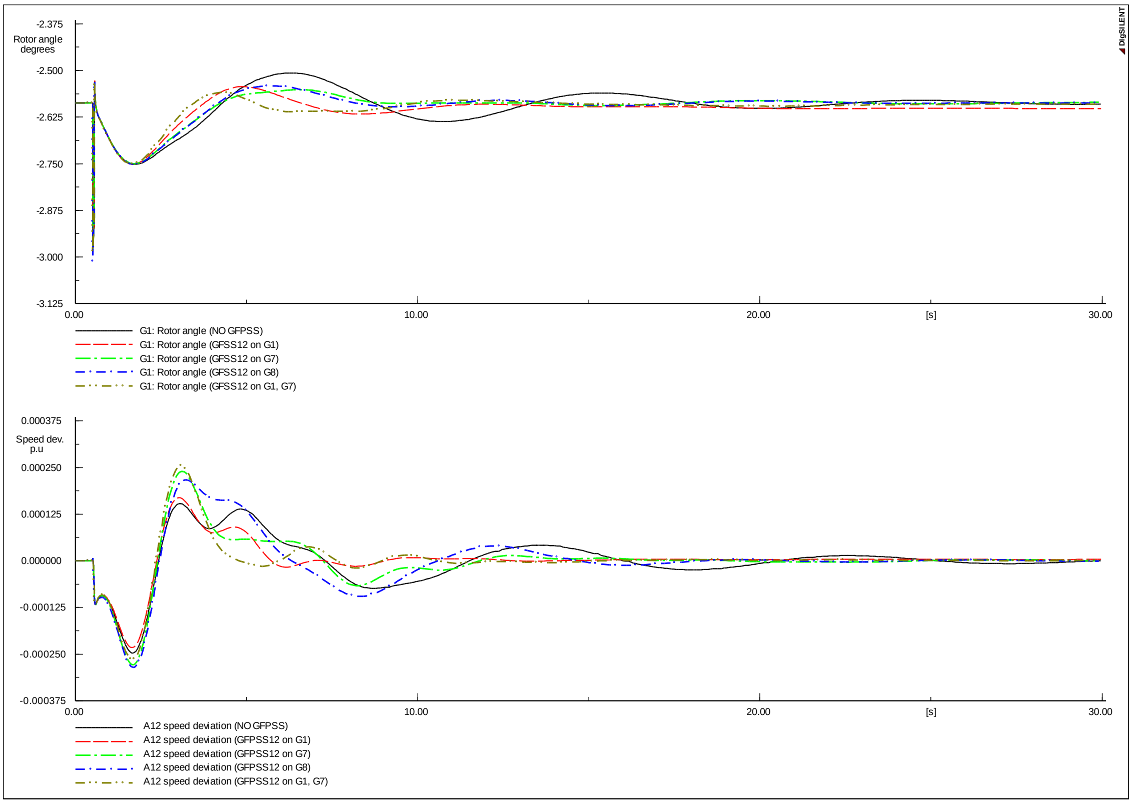

Figure 7-36: Rotor angle and speed deviation signals of generator G1 (3 phase fault at BUS1)

The figure shows that the dynamic response of G1 to the disturbance is enhanced significantly as long as there is a GFPSS signal dispatched to one of the selected generators or to a combination of them (for example G1 and G7 in this case). However, it also confirms that best GFPSS control arrangement is achieved when the GFPSS control loop is implemented on generator G1. This appears clearer in the speed deviation signals of generator G1 (bottom graph). As can be seen, the speed deviation of generator G1 settles quicker with fewer oscillations when the GFPSS control signal is sent to generator G1 with comparison to the other cases when the GFPSS signal is sent to generators G7, G8 or a combination of G1 and G7 (see bottom graph, figure (7-36)).

7.3. Summary

In this chapter the proposed control scheme which involves adding a global control loop to include a wide-area fuzzy logic based power system stabiliser (GFPSS) is implemented for multi-area power systems. The control scheme architecture is generalised such that the wide-area based GFPSS control signal can be produced and dispatched for any power system with any number of clusters and machines (i.e. multi-area power system). The generalised control structure shows how wide-area control signals are extracted from the coherent connected areas and then fed into a number of GFPSS determined by the number of the pre-identified areas or clusters. The control signals produced by the GFPSSs are dispatched to individual generators to provide additional stabilising signals to local PSSs. This control strategy provides the required wide-area based control signals that allow the system's generators to have a wider view of the power system. The additional global control signal allows the entire control scheme to act based on a system wide view rather than acting based on local area information.

The performance of the proposed stabiliser was evaluated by implementing it in two test systems including the 16 generator New England/New York - five clusters test system and the 10 machines - 39 bus test system. In each case, the performance of the GFPSS was tested under a range of operating scenarios and for both small disturbances and large disturbances. Results showed that the proposed scheme has the potential to play a significant role in enhancing power system stability, particularly, stability issues related to power system oscillations or small signal stability.

Chapter 8: Conclusions and Future Work

8.1. Conclusions and Limitations

Power systems networks around the globe are in the process of continuous development which has led to complex interconnected networks. The benefits gained from such complex, widely-spread interconnected networks are related to systems reliability and security of electrical supply as well as to financial benefits. However, other economic, environmental and political issues have put pressure on the electricity market and grid owners and forced them to maximise the utilization of high voltage equipment, which very often lead to their operation closer to the limit. Such an approach of maximum use of systems assets is possible providing that these systems are equipped with well-designed and well-coordinated control and protection schemes to deal with widespread disturbances in the system. As a result, modern interconnected power systems need tools to deal with a wide range of possible system disturbances that often cause widespread system blackouts and supply interruptions. Such tools are mainly in the form of control and protection measures which, when major disturbances occur, play the greatest role to prevent further degradation of the system and minimise the impact of the encountered disturbance. Recent development in communication and measurement technologies have promoted the utilisation of Phasor Measurement Units (PMUs) based Wide-Area Measurement Systems (WAMS) in the area of power systems monitoring, control and protection. The aim of utilising these technologies in power systems is to achieve better management of the system security through advanced control and protection schemes. This Thesis includes a comprehensive survey on recent development in this area. The main focus was put on WAMS based control applications and the different approaches in utilising WAMS technique in the design of wide-area based control schemes that are aimed to enhance the system stability and allow maximum utilisation of power systems.

In this work, the bases of WAMS, which are the Phasor Measurement Units PMUs, were investigated and the basic architecture of a PMU/WAMS based system was illustrated indicating their advantages over the traditional RTU/SCADA only systems.

A general view of WAMS applications in the areas of monitoring, control and protection of power systems was also included. One issue related to power system oscillations, which is believed to cause limitation in the amount of power transfer across transmission lines in increasingly interconnected power systems, was addressed in details. A number of recently developed wide-area based control schemes for power system oscillation damping were investigated considering different design approaches such as; decentralised control strategies, centralised control strategies and multi-agent control strategies. Also, in this research work, the concept of Coherent Clusters (CC), which is related to the oscillation of coherent groups of synchronous generators in multi-machine interconnected power systems, was studied. A number of techniques that identify the coherent clusters in a power system were revised. The achievements of this research that outlined in this thesis can be summarised as follow:

- A new technique that is based on wide-area signal measurements was proposed to determine the coherent clusters in power systems. The proposed technique was developed and tested and the results obtained demonstrated the robustness and the effectiveness of the algorithm in identifying coherent clusters. The accumulated equivalent dynamic response of the formed clusters was also visualised in section 4.4.2. This showed how the formed clusters were distinct from each other in terms of their oscillation phase, oscillation frequency, oscillation magnitude and duration. Chapter 4 describes the techniques and includes detailed discussions of the results obtained. (*The developed technique meets the first objective stated in section 1.4*)

- The identification of coherent clusters was then combined with a mechanism to determine which cluster was more critical for the system stability. This is important, from the control and operation points of view, for the design of stability control schemes to arrest system instabilities. The reason is that, by identifying critical areas, it becomes possible to identify critical tie-lines (those lines that connect the clusters to each other) by visual inspection of the network topology. Such critical lines, where system oscillations are highly observable, can be an important source of providing wide-area based information. This part of the work is presented in chapter 5. (*it contributes to the second objective stated in section 1.4*)

- Information about system oscillations, extracted from signals acquired from these identified coherent clusters and the critical transmission lines connecting them, was used as remote feedback control signals in a newly proposed structure of a WAM based fuzzy logic power system stabiliser (GFPSS). The main objective of the proposed GFPSS was to provide an additional enhanced control signal to local stabilisers that is based on a wide-area view of the power system. The proposed structure allows for better cooperation capability between local control devices as it allows these local controllers to take their control action based on a wide-area view of the system and not based on only locally available feedback control signals. The controller structure and algorithm were presented in details in chapter 6 for a relatively small, simple two-area based power system for ease of design and demonstration. The performance of the designed controller was evaluated in terms of its capability to damp power system oscillations more effectively. It was also evaluated in terms of its effectiveness in enhancing power transfer capability for a given system in section 6.4.1.3. The developed control scheme was shown to have enhanced the transfer capability for this power system by a margin of 26.2 % over the local PSS, which was quite encouraging (*This part meets the third objective stated in section 1.4*)

- The designed controller was then generalised for implementation in multi-area power systems. Implementing the generalised control structure and applying a variety of simulation scenarios using two case studies showed the effectiveness and robustness of the proposed control scheme in enhancing the damping capabilities for system oscillations and improving the overall system stability. Those simulation scenarios, with the controller implementation strategies, were shown in chapter 7. (*This part of the work meets the forth objective stated in section 1.4*)

As is always the case with research based work, there are some inherited limitations. Those limitations include the following:

- One major aspect of WAMS is the information and communication technology infrastructure and architecture. This aspect has not been addressed fully in this piece of work and may require further investigations.

- It is shown from the results that the GFPSS placement was an essential part of the control scheme for improved system performance. Results showed that if the GFPSS wide-area signal was sent to randomly selected generators, then this had a negative impact on the overall system performance and caused system instability instead. Therefore, establishment of a GFPSS signal dispatch scheme based on system analysis is very important for enhanced performance. Selection of which of the system generators are to receive the wide-area based GFPSS signal is an area that needs further investigation.

8.2. Future Work

It has been demonstrated throughout the chapters of this thesis that power systems are large, interconnected, nonlinear systems where system wide-area instabilities can occur and threaten the operational security of the system. Such instability phenomena can lead to wide-area system blackouts which cause considerable economic costs as well as social impacts on electricity consumers. It has also been shown that due to deregulation of electricity market and increase in electricity demand, power systems around the globe are being forced to operate closer than ever to their stability limits. This is because the construction of new transmission lines to meet the ever-increasing consumer demand is lagging behind due to economic as well as environmental concerns. Stressed operation of transmission networks and heavy power flows across transmission interconnections weakens the operational security of the power system, especially with respect to oscillatory and angle stability phenomenon. In other words, the steady increase of electricity demand with no, or little, corresponding expansion of transmission networks is pushing power systems to operate closer to their stability limits. This causes concerns about the possibility of the rise of oscillatory behaviours between interconnected areas; a problem that has been, in the past, dealt with by conservative operation of power systems (i.e. by keeping conservative stability margins and not pushing high amounts of power across the tie-lines or the interconnections); an option that should no longer be acceptable.

In this thesis a new control scheme that combines the concept of coherent clusters with WAM based control techniques was proposed. The results were encouraging, meeting the research objectives set at the start of this work; that is to develop a wide-area based control scheme to enhance overall transmission stability and allow for better utilisation of transmission assets. Nonetheless, as is always the case, considerable improvements can be added to the proposed approach to make it more effective, applicable, efficient, and more importantly, to overcome some of its limitations. The areas of possible future improvement are summarised as follow:

- The communication infrastructure is a critical component in the architecture of WAMS based control schemes. This is because in a typical WAMS system the PMUs devices are geographically spread over a wide area. The PMUs are connected to a central control centre or several control centres over a communication network which may cause effects of synchronisation inaccuracy and signal time delay [93]. Therefore, the communication network is an important part of the system structure since the data quality of PMU measurements collected from remote sites would largely depend on the capabilities of the communications infrastructure. Several research papers have suggested the use of dedicated fibre optic links as the main communication media of PMU communication networks [94] [95]. This is for the sake of minimising the effects of time delay which an important measure of the success of PMU based applications. The other argument in favour of cost efficiency is to share the existing wide-area communication network with SCADA systems as well as other applications. In such a network, the traffic from PMUs would be accompanied by traffic from substations' RTUs. The traffic would be prioritized according to their relative importance. This allows for flexibility in configuration as well as reduction in cost and improved efficiency in terms of maintenance and operation. This is a suggested area for further work and research.

- Another area that requires further investigation to improve the performance of the developed GFPSS control scheme is the allocation strategy which identifies the specific units to which the GFPSS wide-area based control signal is dispatched. The techniques introduced in chapter 5 to identify the key critical areas to the system stability can be taken as the framework to establish a strategy that enables the identification of key units to implement the WAM based stability enhancement control scheme.

- Renewable energy based generation technologies are becoming more integrated within power systems. They are mostly connected at sub-transmission or distribution levels and are normally dispersed throughout the network. This causes a number of benefits and challenges for power system operators as integration of renewable energy resources in distribution networks makes a distribution system more dynamic. In many countries wind power has proven to be the fastest growing power generation technology [96]. With increased penetration of these wind turbines, power systems dominated by synchronous machines will experience a change in dynamics and operational characteristics [97], [98]. Therefore the impact of increased penetration of such technologies on system stability needs to be addressed. Hence, investigating the impact of the integration that a large number of wind farms could have on the stability of the power system is recommended for future work. Two main areas related to this work that need to be addressed are:
    1- The formation of the coherent clusters within a given system when a large number of wind farms are included in the study.
    2- The impact of wind power intermittency and uncertainty on the formation of coherent clusters.
    3- The impact of increased penetration of wind generation on the performance of the GFPSS control loops.

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Appendices

Appendix A1: Data of the 16 generator 68 bus New England / New York test system

Line data:

From bus	To bus	Resistance (p.u)	Reactance (p.u)	Line charging (p.u)	Tap ration
1	2	0.007	0.0822	0.3493	0
1	30	0.0008	0.0074	0.48	0
2	3	0.0013	0.0151	0.2572	0
2	25	0.007	0.0086	0.146	0
2	53	0	0.0181	0	1.025
3	4	0.0013	0.0213	0.2214	0
3	18	0.0011	0.0133	0.2138	0
4	5	0.0008	0.0128	0.1342	0
4	14	0.0008	0.0129	0.1382	0
5	6	0.0002	0.0026	0.0434	0
5	8	0.0008	0.0112	0.1476	0
6	7	0.0006	0.0092	0.113	0
6	11	0.0007	0.0082	0.1389	0
6	54	0	0.025	0	1.07
7	8	0.0004	0.0046	0.078	0
8	9	0.0023	0.0363	0.3804	0
9	30	0.0019	0.0183	0.29	0
10	11	0.0004	0.0043	0.0729	0
10	13	0.0004	0.0043	0.0729	0
10	55	0	0.02	0	1.07
12	11	0.0016	0.0435	0	1.06
12	13	0.0016	0.0435	0	1.06
13	14	0.0009	0.0101	0.1723	0
14	15	0.0018	0.0217	0.366	0
15	16	0.0009	0.0094	0.171	0
16	17	0.0007	0.0089	0.1342	0
16	19	0.0016	0.0195	0.304	0
16	21	0.0008	0.0135	0.2548	0
16	24	0.0003	0.0059	0.068	0
17	18	0.0007	0.0082	0.1319	0
17	27	0.0013	0.0173	0.3216	0
19	20	0.0007	0.0138	0	1.06

19	56	0.0007	0.0142	0	1.07
20	57	0.0009	0.018	0	1.009
21	22	0.0008	0.014	0.2565	0
22	23	0.0006	0.0096	0.1846	0
22	58	0	0.0143	0	1.025
23	24	0.0022	0.035	0.361	0
23	59	0.0005	0.0272	0	0
25	26	0.0032	0.0323	0.531	0
25	60	0.0006	0.0232	0	1.025
26	27	0.0014	0.0147	0.2396	0
26	28	0.0043	0.0474	0.7802	0
26	29	0.0057	0.0625	1.029	0
28	29	0.0014	0.0151	0.249	0
29	61	0.0008	0.0156	0	1.025
9	30	0.0019	0.0183	0.29	0
9	36	0.0022	0.0196	0.34	0
9	36	0.0022	0.0196	0.34	0
36	37	0.0005	0.0045	0.32	0
34	36	0.0033	0.0111	1.45	0
35	34	0.0001	0.0074	0	0.946
33	34	0.0011	0.0157	0.202	0
32	33	0.0008	0.0099	0.168	0
30	31	0.0013	0.0187	0.333	0
30	32	0.0024	0.0288	0.488	0
1	31	0.0016	0.0163	0.25	0
31	38	0.0011	0.0147	0.247	0
33	38	0.0036	0.0444	0.693	0
38	46	0.0022	0.0284	0.43	0
46	49	0.0018	0.0274	0.27	0
1	47	0.0013	0.0188	1.31	0
47	48	0.0025	0.0268	0.4	0
47	48	0.0025	0.0268	0.4	0
48	40	0.002	0.022	1.28	0
35	45	0.0007	0.0175	1.39	0
37	43	0.0005	0.0276	0	0
43	44	0.0001	0.0011	0	0
44	45	0.0025	0.073	0	0
39	44	0	0.0411	0	0
39	45	0	0.0839	0	0
45	51	0.0004	0.0105	0.72	0
50	52	0.0012	0.0288	2.06	0
50	51	0.0009	0.0221	1.62	0

49	52	0.0076	0.1141	1.16	0
52	42	0.004	0.06	2.25	0
42	41	0.004	0.06	2.25	0
41	40	0.006	0.084	3.15	0
31	62	0	0.026	0	1.04
32	63	0	0.013	0	1.04
36	64	0	0.0075	0	1.04
37	65	0	0.0033	0	1.04
41	66	0	0.0015	0	1
42	67	0	0.0015	0	1
52	68	0	0.003	0	1
1	27	0.032	0.32	0.41	1

Machines dynamic data:

Unit No.	Base MVA	X1 (p.u)	Ra (p.u)	Xd (p.u)	X'd (p.u)	X"d (p.u)	T'd (sec)	T"d (sec)	Xq (p.u)	X'q (p.u)	X"q (p.u)	T'q (sec)	T"q (sec)	H (sec)
1	1800	0	0	2	0.6	0.5	10	0.05	1.2	0.5	0.45	1.5	0.04	2.33
2	610	0	0	2	0.4	0.3	6.6	0.05	1.7	0.37	0.31	1.5	0.04	4.95
3	721	0	0	2	0.4	0.3	5.7	0.05	1.7	0.36	0.32	1.5	0.04	4.96
4	687	0	0	2	0.3	0.2	5.7	0.05	1.8	0.27	0.24	1.5	0.04	4.16
5	545	0	0	2	0.4	0.3	5.4	0.05	1.7	0.33	0.27	0.4	0.04	4.77
6	709	0	0	2	0.4	0.3	7.3	0.05	1.7	0.32	0.28	0.4	0.04	4.91
7	610	0	0	2	0.3	0.2	5.7	0.05	1.8	0.27	0.24	1.5	0.04	4.33
8	621	0	0	2	0.4	0.3	6.7	0.05	1.7	0.31	0.28	0.4	0.04	3.92
9	855	0	0	2	0.5	0.4	4.8	0.05	1.8	0.43	0.38	2	0.04	4.04
10	1065	0	0	2	0.5	0.4	9.4	0.05	1.2	0.48	0.43	1.5	0.04	2.91
11	1406	0	0	2	0.3	0.2	4.1	0.05	1.7	0.21	0.17	1.5	0.04	2.01
12	1782	0	0	2	0.6	0.4	7.4	0.05	1.7	0.5	0.45	1.5	0.04	5.18
13	12162	0	0	2	0.3	0.2	5.9	0.05	1.7	0.3	0.24	1.5	0.04	4.08
14	10000	0	0	2	0.3	0.2	4.1	0.05	1.7	0.25	0.23	1.5	0.04	3
15	10000	0	0	2	0.3	0.2	4.1	0.05	1.7	0.25	0.23	1.5	0.04	3
16	10112	0	0	2	0.4	0.3	7.8	0.05	1.7	0.3	0.28	1.5	0.04	4.45

Stator leakage reactance Xl (p.u)

Stator resistance Ra (pu)

d-axis synchronous reactance Xd (p.u)

d-axis transient reactance X'd (p.u)

d-axis sub-transient reactance X"d (p.u)

d-axis open-circuit time constant T'd (sec)

d-axis open-circuit sub-transient time constant T"d (sec)

q-axis synchronous reactance Xq (p.u)

q-axis transient reactance X'q (p.u)

q-axis sub-transient reactance X''q (p.u)

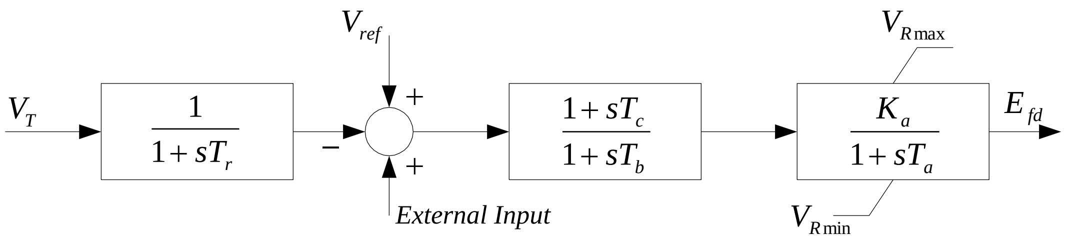
q-axis open-circuit time constant T'q (sec)

q-axis open circuit sub-transient time constant T''q (sec)

Inertia constant H (sec)

Exciter System Data:

Machine No.	Tr (sec)	Ka (pu)	Ta (sec)	Tb (sec)	Tc (sec)	Vrmax (pu)	Vrmin (pu)
1	0	100	0.05	0	0	5	-5
2	0	100	0.05	0	0	5	-5
3	0	100	0.05	0	0	5	-5
4	0	100	0.05	0	0	5	-5
5	0	100	0.05	0	0	5	-5
6	0	100	0.05	0	0	5	-5
7	0	100	0.05	0	0	5	-5
8	0	100	0.05	0	0	5	-5
9	0	100	0.05	0	0	5	-5
10	0	100	0.05	0	0	5	-5
11	0	100	0.05	0	0	5	-5
12	0	100	0.05	0	0	5	-5
13	0	100	0.05	0	0	5	-5
14	0	100	0.05	0	0	5	-5
15	0	100	0.05	0	0	5	-5
16	0	100	0.05	0	0	5	-5



Block diagram of the exciter model

Transducer filter time constant Tr (sec)

Voltage regulator gain Ka (p.u)

Voltage regulator time constant Ta (sec)

Transient gain reduction time constant Tb (sec)

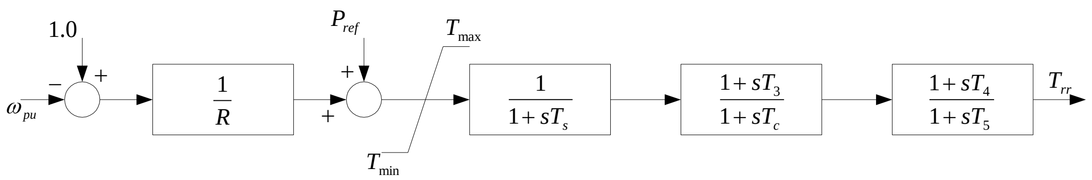
Transient gain reduction time constant Tc (sec)

Maximum voltage regulator output Vrmax (p.u)

Minimum voltage regulator output Vrmin (p.u)

Speed governors' data:

Machine number	wf (pu)	1/R (pu)	Tmax (sec)	Ts (sec)	Tc (sec)	T3 (sec)	T4 (sec)	T5 (sec)
1	1	25	1	0.1	0.5	0	1.25	5
2	1	25	1	0.1	0.5	0	1.25	5
3	1	25	1	0.1	0.5	0	1.25	5
4	1	25	1	0.1	0.5	0	1.25	5
5	1	25	1	0.1	0.5	0	1.25	5
6	1	25	1	0.1	0.5	0	1.25	5
7	1	25	1	0.1	0.5	0	1.25	5
8	1	25	1	0.1	0.5	0	1.25	5
9	1	25	1	0.1	0.5	0	1.25	5
10	1	25	1	0.1	0.5	0	1.25	5
11	1	25	1	0.1	0.5	0	1.25	5
12	1	25	1	0.1	0.5	0	1.25	5
13	1	25	1	0.1	0.5	0	1.25	5
14	1	25	1	0.1	0.5	0	1.25	5
15	1	25	1	0.1	0.5	0	1.25	5
16	1	25	1	0.1	0.5	0	1.25	5



Block diagram of the turbine speed governor

Speed set point ω_f (p.u)

Steady state gain 1/R (p.u)

Maximum power order Tmax (p.u) on generator base

Servo time constant Ts (sec)

Governor time constant Tc (sec)

Transient gain time constant T3 (sec)

HP section time constant T4 (sec)

Reheater time constant T5 (sec)

Appendix A2: Data of the 10 machines-39-bus IEEE test system

Line data:

From Bus	To Bus	Resistance	Reactance	Susceptance
1	2	0.0035	0.0411	0.6987
1	39	0.001	0.025	0.75
2	3	0.0013	0.0151	0.2572
2	25	0.007	0.0086	0.146
3	4	0.0013	0.0213	0.2214
3	18	0.0011	0.0133	0.2138
4	5	0.0008	0.0128	0.1342
4	14	0.0008	0.0129	0.1382
5	6	0.0002	0.0026	0.0434
5	8	0.0008	0.0112	0.1476
6	7	0.0006	0.0092	0.113
6	11	0.0007	0.0082	0.1389
7	8	0.0004	0.0046	0.078
8	9	0.0023	0.0363	0.3804
9	39	0.001	0.025	1.2
10	11	0.0004	0.0043	0.0729
10	13	0.0004	0.0043	0.0729
13	14	0.0009	0.0101	0.1723
14	15	0.0018	0.0217	0.366
15	16	0.0009	0.0094	0.171
16	17	0.0007	0.0089	0.1342
16	19	0.0016	0.0195	0.304
16	21	0.0008	0.0135	0.2548
16	24	0.0003	0.0059	0.068
17	18	0.0007	0.0082	0.1319
17	27	0.0013	0.0173	0.3216
21	22	0.0008	0.014	0.2565
22	23	0.0006	0.0096	0.1846
23	24	0.0022	0.035	0.361
25	26	0.0032	0.0323	0.513
26	27	0.0014	0.0147	0.2396
26	28	0.0043	0.0474	0.7802
26	29	0.0057	0.0625	1.029
28	29	0.0014	0.0151	0.249
12	11	0.0016	0.0435	0.0000
12	13	0.0016	0.0435	0.0000
6	31	0.0000	0.0250	0.0000
10	32	0.0000	0.0200	0.0000
19	33	0.0007	0.0142	0.0000
20	34	0.0009	0.0180	0.0000
22	35	0.0000	0.0143	0.0000
23	36	0.0005	0.0272	0.0000
25	37	0.0006	0.0232	0.0000

2	30	0.0000	0.0181	0.0000
29	38	0.0008	0.0156	0.0000
19	20	0.0007	0.0138	0.0000

Machines data:

Unit No.	H	R_a	x'_d	x'_q	x_d	x_q	T'_{do}	T'_{qo}	x_l
1	500	0	0.006	0.008	0.02	0.019	7.0	0.7	0.003
2	30.3	0	0.0697	0.17	0.295	0.282	6.56	1.5	0.035
3	35.8	0	0.0531	0.0876	0.2495	0.237	5.7	1.5	0.0304
4	28.6	0	0.0436	0.166	0.262	0.258	5.69	1.5	0.0295
5	26.0	0	0.132	0.166	0.67	0.62	5.4	0.44	0.054
6	34.8	0	0.05	0.0814	0.254	0.241	7.3	0.4	0.0224
7	26.4	0	0.049	0.186	0.295	0.292	5.66	1.5	0.0322
8	24.3	0	0.057	0.0911	0.29	0.28	6.7	0.41	0.028
9	34.5	0	0.057	0.0587	0.2106	0.205	4.79	1.96	0.0298
10	42	0	0.031	0.008	0.1	0.069	10.2	0	0.0125

Exciter System Data:

Unit No.	T_R	K_A	T_A	T_B	T_C	$V_{setpoint}$	E_{fdMax}	E_{fdMin}
1	0.01	200	0.015	10	1	1.03	5	-5
2	0.01	200	0.015	10	1	0.982	5	-5
3	0.01	200	0.015	10	1	0.9831	5	-5
4	0.01	200	0.015	10	1	0.9972	5	-5
5	0.01	200	0.015	10	1	1.0123	5	-5
6	0.01	200	0.015	10	1	1.0493	5	-5
7	0.01	200	0.015	10	1	1.0635	5	-5
8	0.01	200	0.015	10	1	1.0278	5	-5
9	0.01	200	0.015	10	1	1.0265	5	-5
10	0.01	200	0.015	10	1	1.0475	5	-5

Speed governors' data:

Machine number	wf (pu)	1/R (pu)	Tmax (sec)	Ts (sec)	Tc (sec)	T3 (sec)	T4 (sec)	T5 (sec)
1	1	200	1	0.1	0.5	0	1.25	5
2	1	200	1	0.1	0.5	0	1.25	5
3	1	200	1	0.1	0.5	0	1.25	5
4	1	200	1	0.1	0.5	0	1.25	5
5	1	200	1	0.1	0.5	0	1.25	5
6	1	200	1	0.1	0.5	0	1.25	5
7	1	200	1	0.1	0.5	0	1.25	5
8	1	200	1	0.1	0.5	0	1.25	5
9	1	200	1	0.1	0.5	0	1.25	5
10	1	200	1	0.1	0.5	0	1.25	5

Appendix A3: Data of the two-area four machine test system

Line data:

From Bus	To Bus	Line length km	Resistance pu/km	Reactance pu/km	Susceptance pu/km
5	6	25	0.0001	0.001	0.000175
6	7	10	0.0001	0.001	0.000175
7	8	110	0.0001	0.001	0.000175
8	9	110	0.0001	0.001	0.000175
9	10	10	0.0001	0.001	0.000175
10	11	25	0.0001	0.001	0.000175

Machine data:

Unit No.	H	Ra (p.u)	Xl (p.u)	Xd (p.u)	Xq (p.u)	X'd (pu)	X'q (pu)	X"d (pu)	X"q (p.u)	T'd (sec)	T"d (sec)	T'q (sec)	T"q (sec)
1	6.5	0.0025	0.2	1.8	1.7	0.3	0.55	0.25	0.25	8.0	0.03	0.4	0.05
2	6.5	0.0025	0.2	1.8	1.7	0.3	0.55	0.25	0.25	8.0	0.03	0.4	0.05
3	6.175	0.0025	0.2	1.8	1.7	0.3	0.55	0.25	0.25	8.0	0.03	0.4	0.05
4	6.175	0.0025	0.2	1.8	1.7	0.3	0.55	0.25	0.25	8.0	0.03	0.4	0.05

Appendix A4: Related Publications

1. Alsafih, H.A.; Dunn, R.; , "Determination of coherent clusters in a multi-machine power system based on wide-area signal measurements," *Power and Energy Society General Meeting, 2010 IEEE* , vol., no., pp.1-8, 25-29 July 2010

2. Alsafih, H.A.; Dunn, R.W.; , "Identification of critical areas for potential wide- area based control in complex power systems based on coherent clusters," *Universities Power Engineering Conference (UPEC), 2010 45th International* , vol., no., pp.1-6, Aug. 31 2010-Sept. 3 2010

3. Alsafih, H. A.; Dunn, R. W.; , "Performance of Wide-Area based Fuzzy Logic Power System Stabilizer," *Universities' Power Engineering Conference (UPEC), Proceedings of 2011 46th International* , vol., no., pp.1-6, 5-8 Sept. 2011